ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Biological Actuators.
The muscle

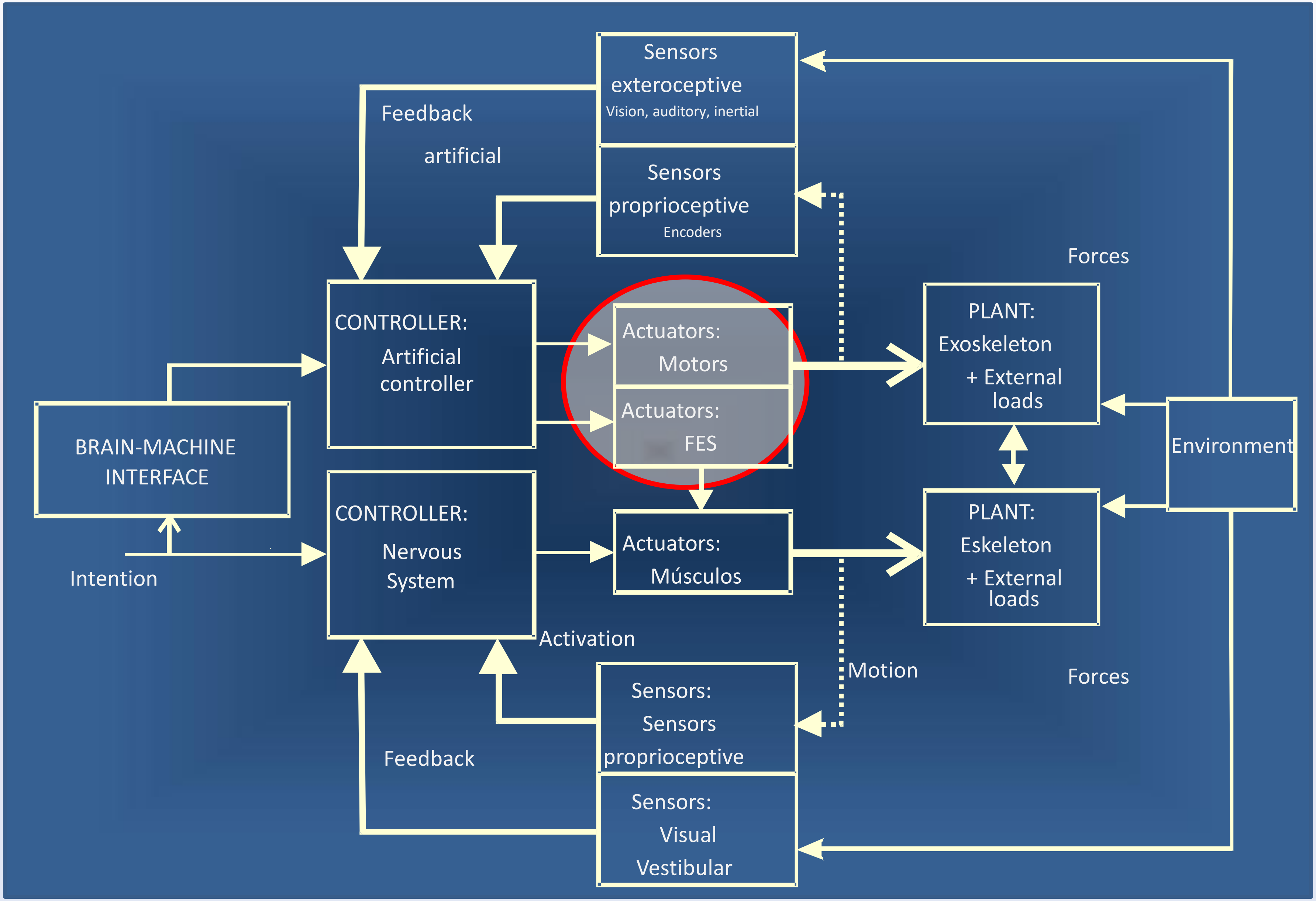
Arturo Forner-Cordero
(aforner@usp.br)
Laboratorio de Biomecatrônica
Departamento de Engenharia Mecatrônica e Systems Mecánicos

Contents

Introduction

- Justification
  - Understanding the system
  - Intervention:
    - Rehabilitation
    - Training
  - Functional compensation
  - Actuation on the muscle
  - Development of bioinspired actuation systems

Motor compensation



Sensors exteroceptive

Vision, auditory, inertial

Feedback

artificial

Sensors proprioceptive

Encoders

Forces

CONTROLLER:

Artificial controller

Actuators:

Motors

Actuators:

FES

PLANT:

Exoskeleton

+ External loads

BRAIN-MACHINE INTERFACE

Environment

CONTROLLER:

Nervous System

Actuators:

Músculos

PLANT:

Eskeleton

+ External loads

Intention

Activation

Motion

Forces

Sensors:

Sensors proprioceptive

Feedback

Sensors:

Visual

Vestibular

Goals

- Biological actuators:
  - Muscle physiology
  - Mucle function and properties
  - Muscle models
- Artificial actuators:
  - Actuators overview:
    - Functional compensation
    - Biorobotics and biomimetic robots
    - Artificial drive of natural actuators

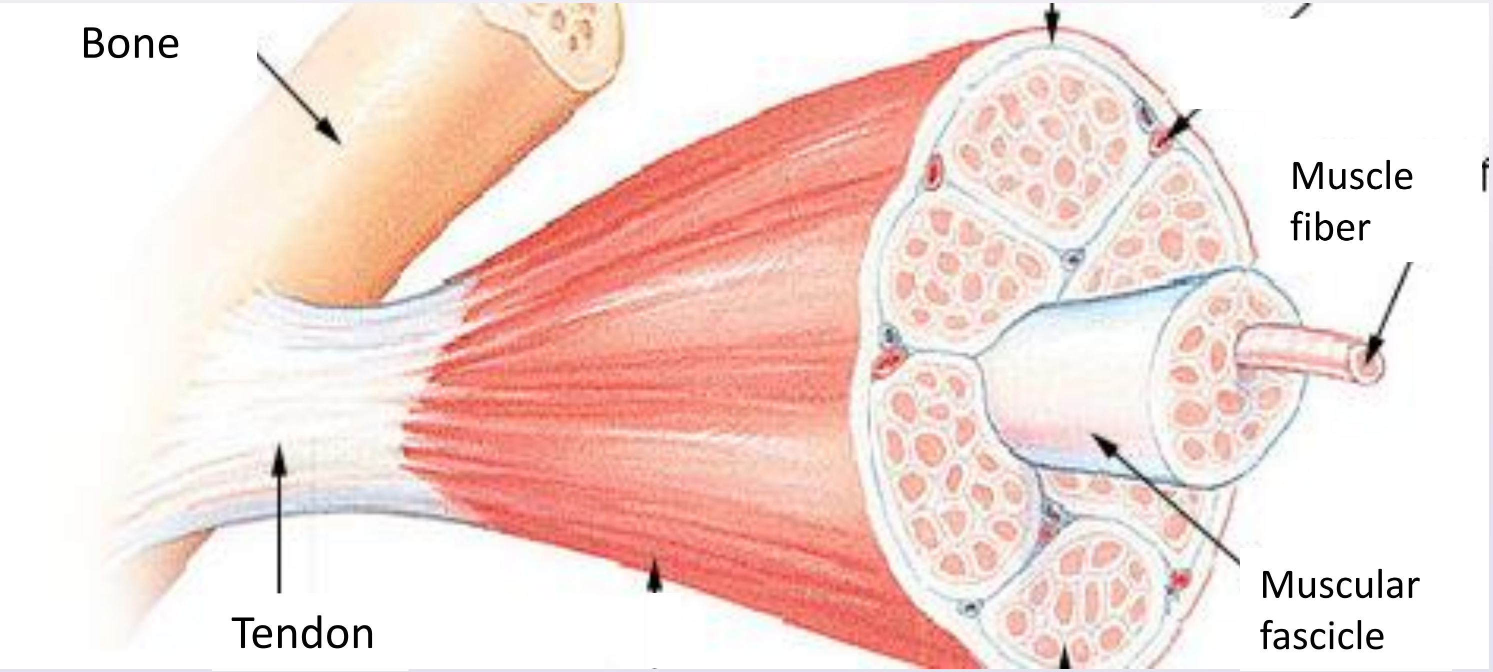
Contents

1. Introduction: Justification and goals

2. Biological actuators
    - Organization and structure
    - Functioning principles
    - Muscle models
        - Hill
        - Cross-bridge

3. Robotic artificial actuators. Biomimetism
    - Artificial actuators
    - Actuator comparison: biological vs artificial
    - Actuation of a system of biological actuators

The muscle

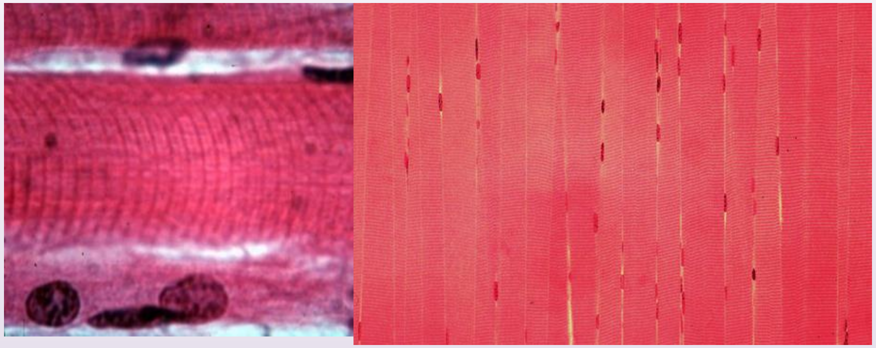


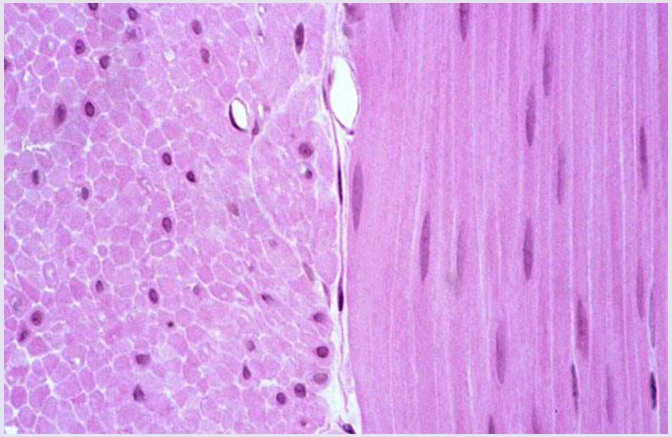
Muscles

- The human body has more than 400 skeletal muscles
  - 40-50% of total body weight
- Skeletal muscle functions:
  - Force production:
    - Locomotion
    - Postural support
    - Breathing
  - Heat production
- Muscle microstructure:
  - Sarcoleme: Membrane of the mucle cell
  - Myofibrils
    - Actin
    - Myosin
    - Titin

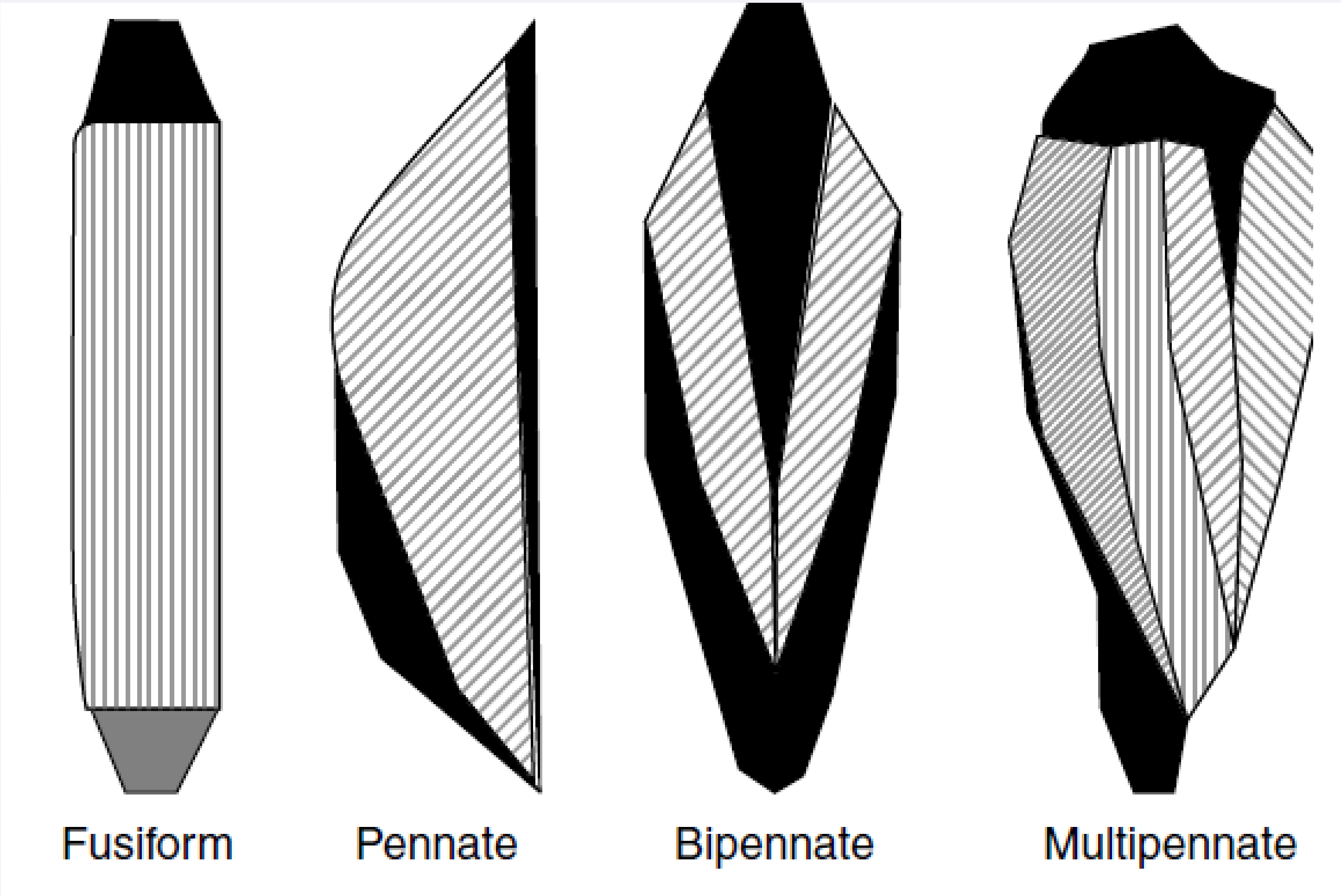
Muscles

- Types:
  - Skeletal:
    - Striate
    - Volunteer
  - Cardiac:
    - Striate
    - Involuntary
  - Smooth:
    - Involuntary
    - Slow

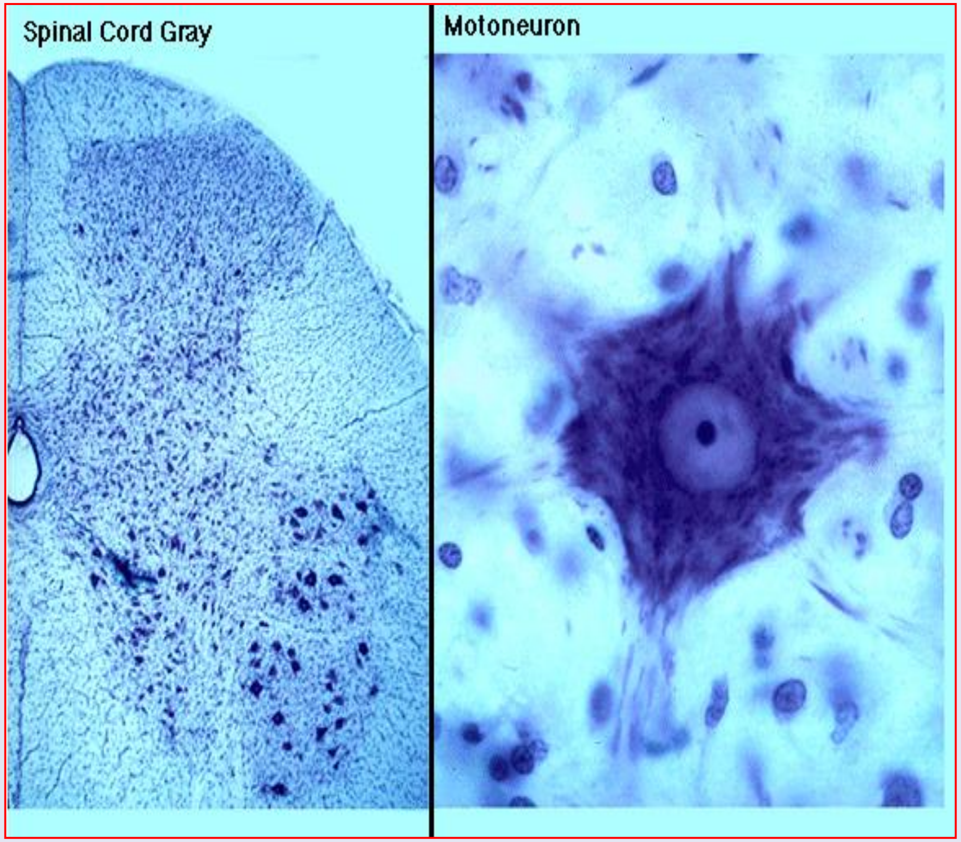




Fiber layout



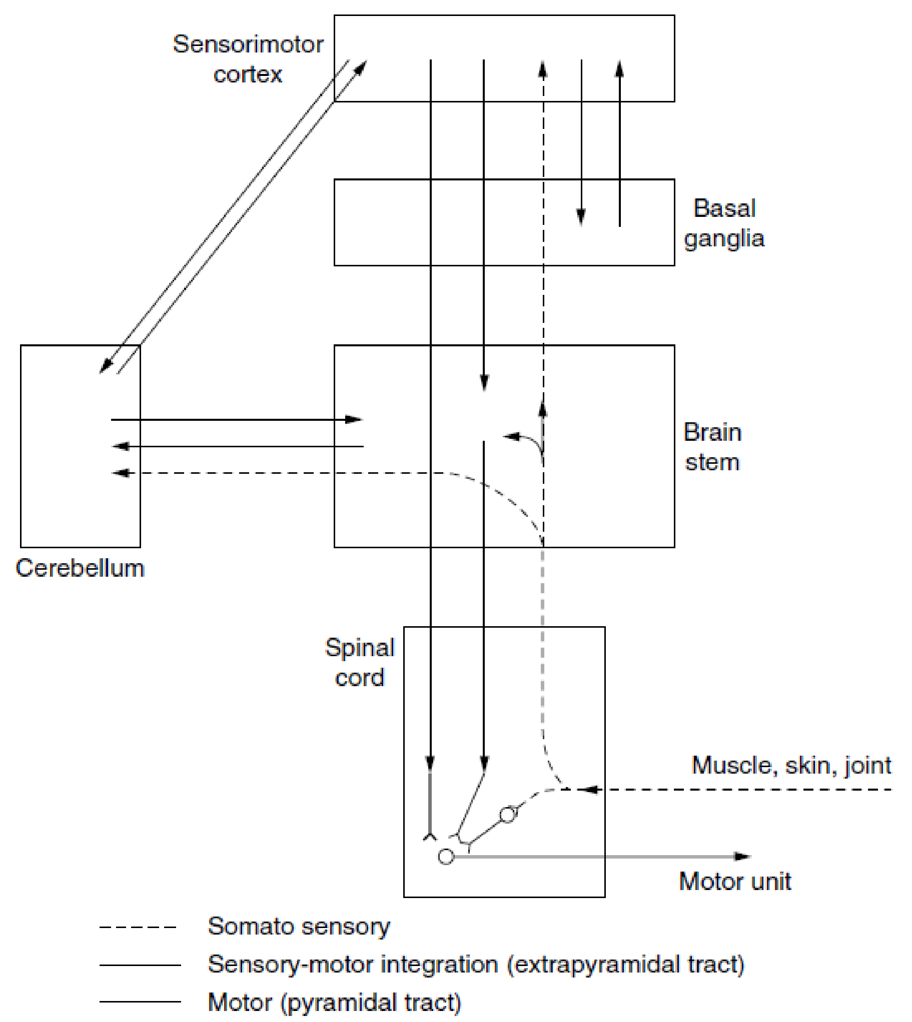
Motor-neurons



- alpha e gamma

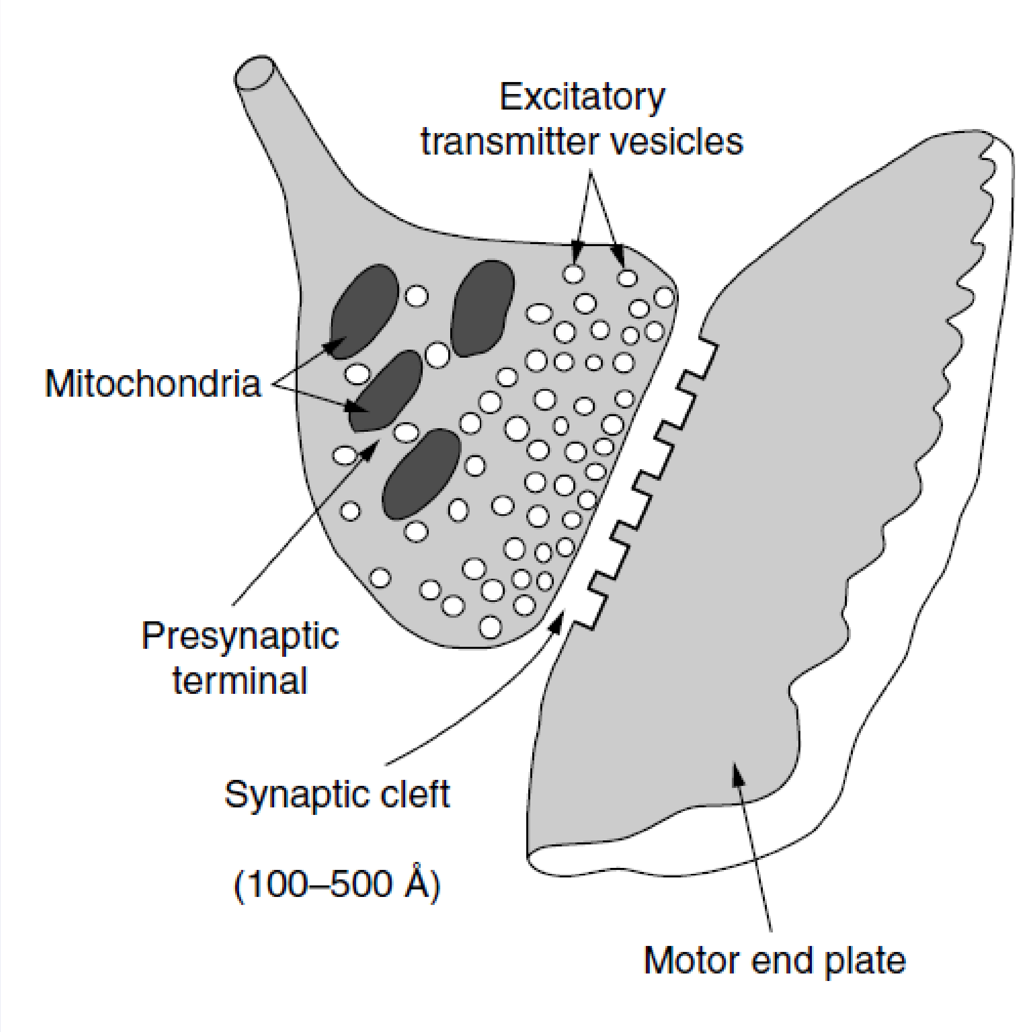
- Alpha:
  - Extrafusal
  - 60-80 m/s
- Gamma:
  - Intrafusal
  - 25-60 m/s
- Motor unit: Motoneuron and the innervated muscle fibers

Muscle control architecture



Adapted from McMahon, 1984. Muscles, Reflexes and Locomotion.

Motor plate

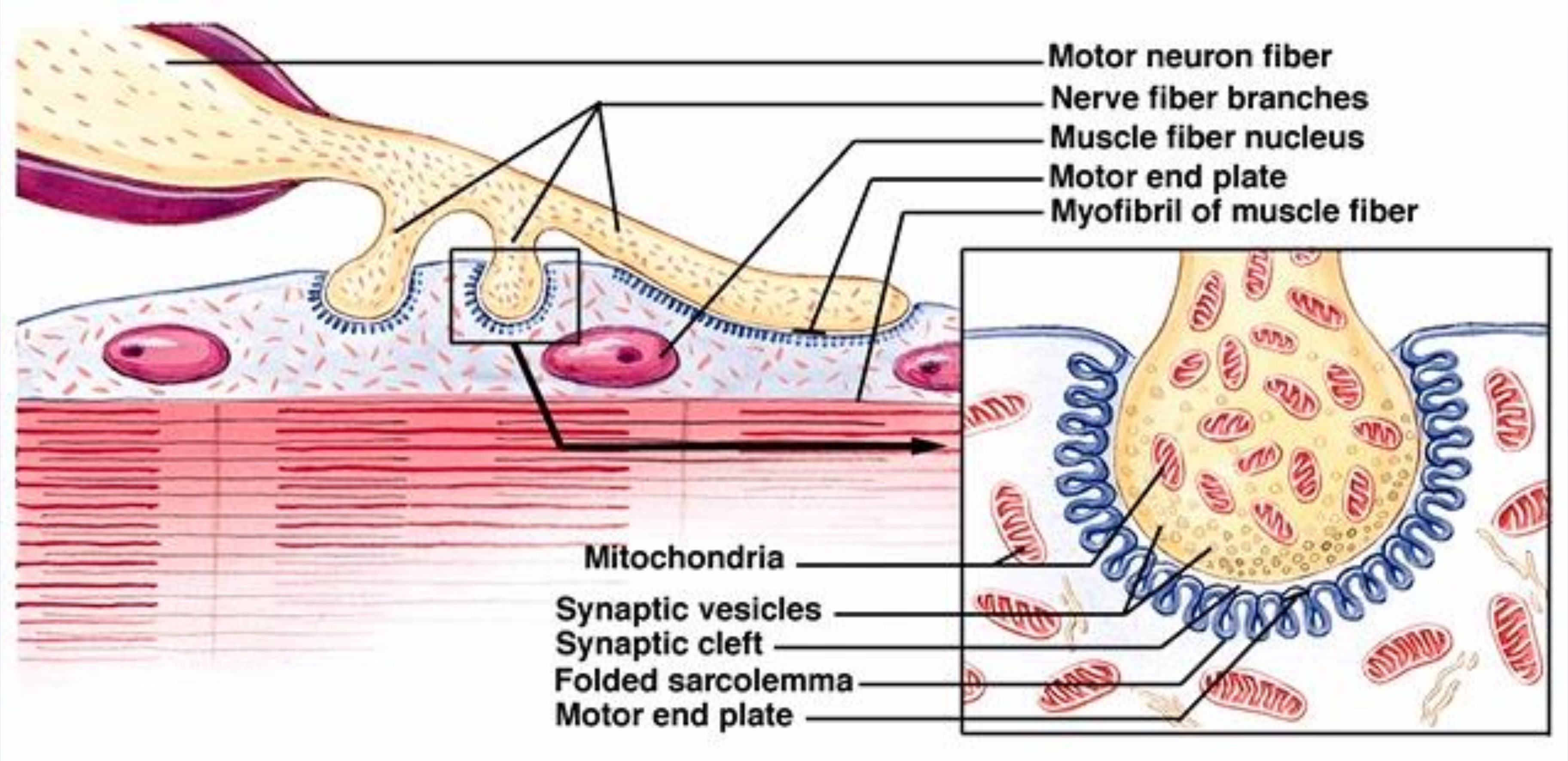


Guyton, A.C., 1971. *Textbook of Medical Physiology* , Philadelphia: W.B. Saunders

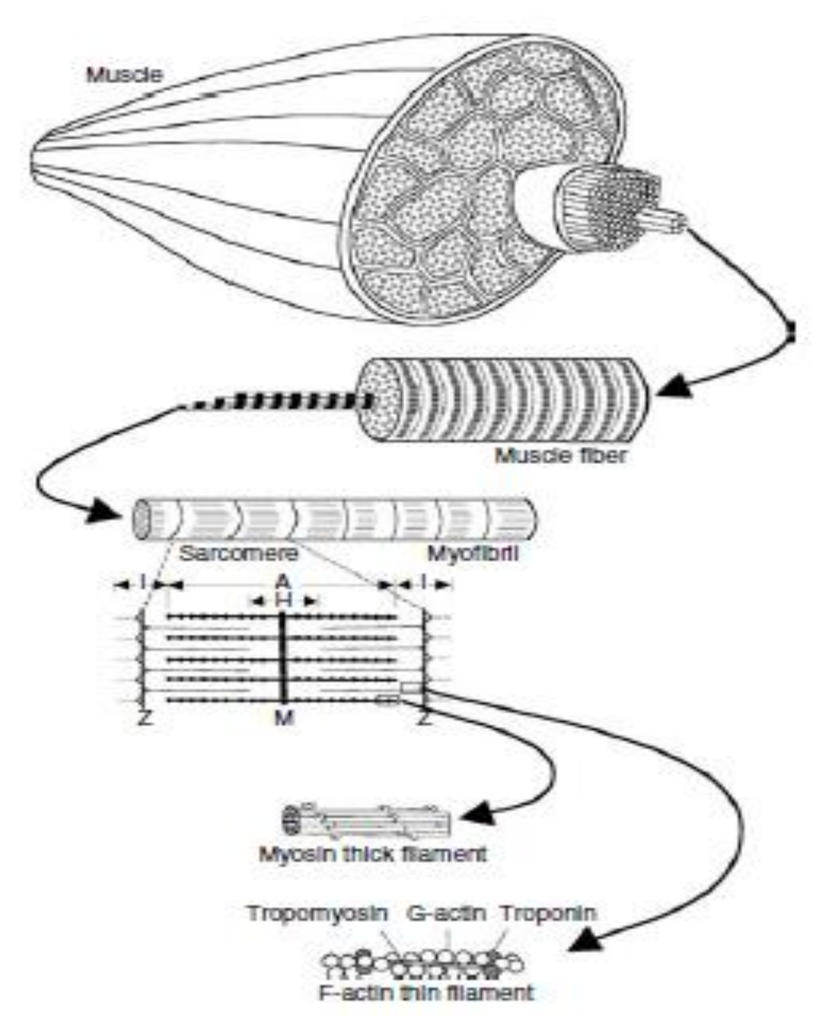
Neuromuscular junction

- Neuron-muscle fiber
  - Neuromuscular cleft
- Motor plate
  - Bag around the moto-neuron formed by the sarcolemma
- Acetylcholine is released by the neuron:
  - Triggers an action potential in the motor plate (EPP)
  - Depolarization of the muscle fiber

Neuromuscular junction



Muscle structure



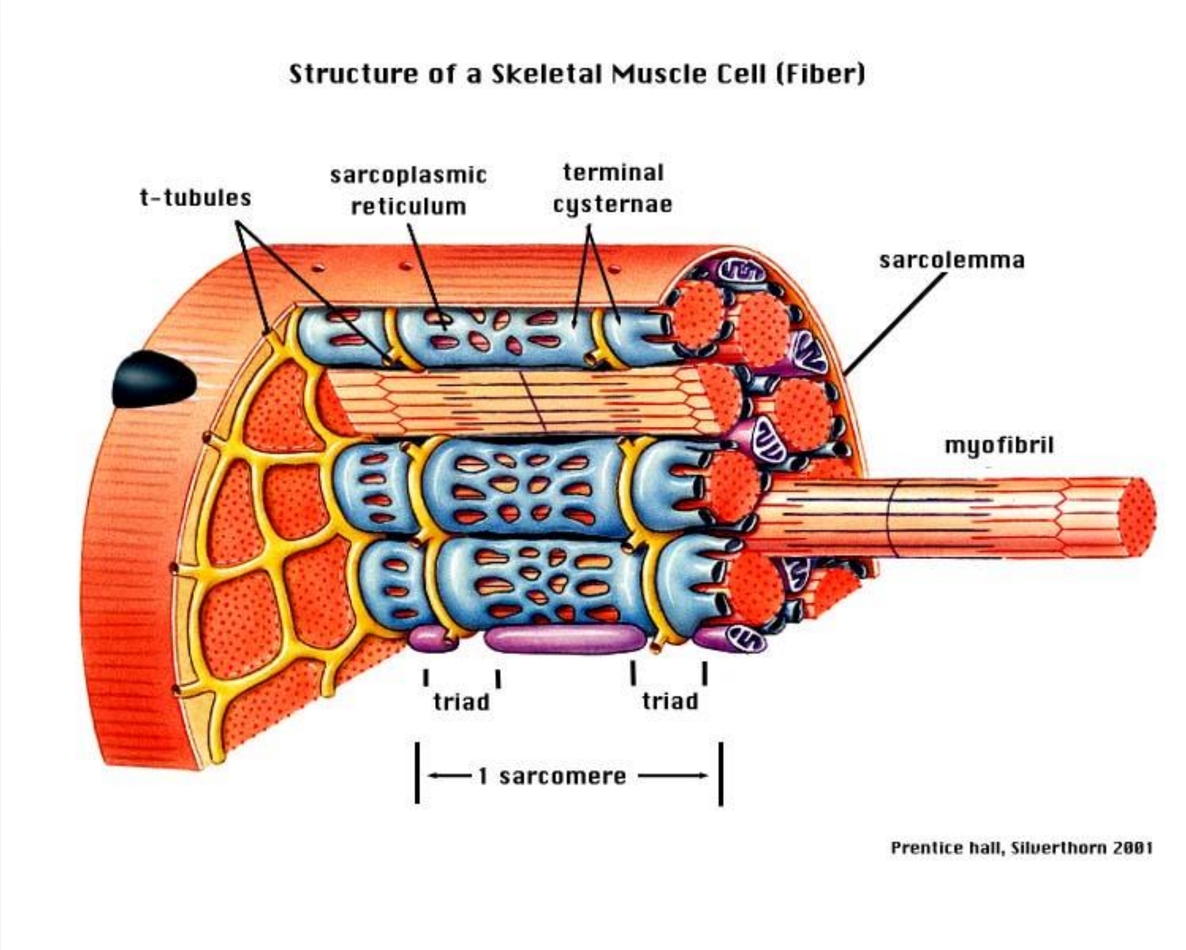
McMahon, 1984. Muscles, Reflexes and Locomotion.

Muscle structure

- Myofibers. Cells with several nuclei:
  - Diameter: 10 - 60 µm
  - Length: 5 - 140 mm
- Myofibrils 1000 - 8000 por fiber.
  - Diameter: 1 µm
  - Contraction mechanism: Myofilaments
- Myofilaments
  - Thick: myosin (long proteins)
  - Thin: actin (globular proteins)

Muscle structure

- Sarcomere
- actin
- myosin
- *Cross-bridges*



Structure of a Skeletal Muscle Cell (Fiber)

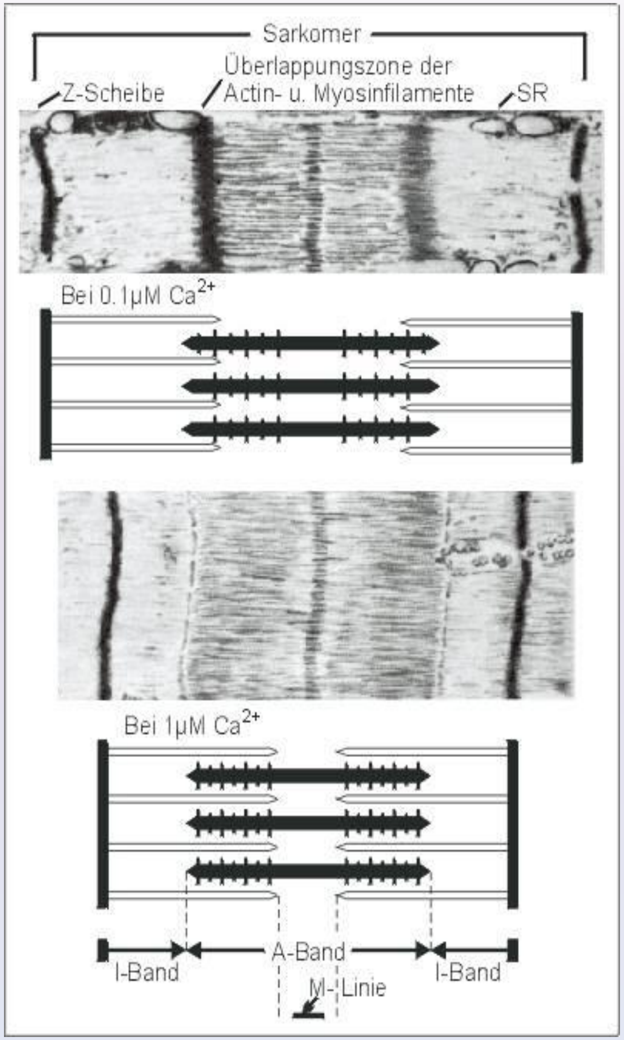
Prentice hall, Silverthorn 2001

Muscle structure

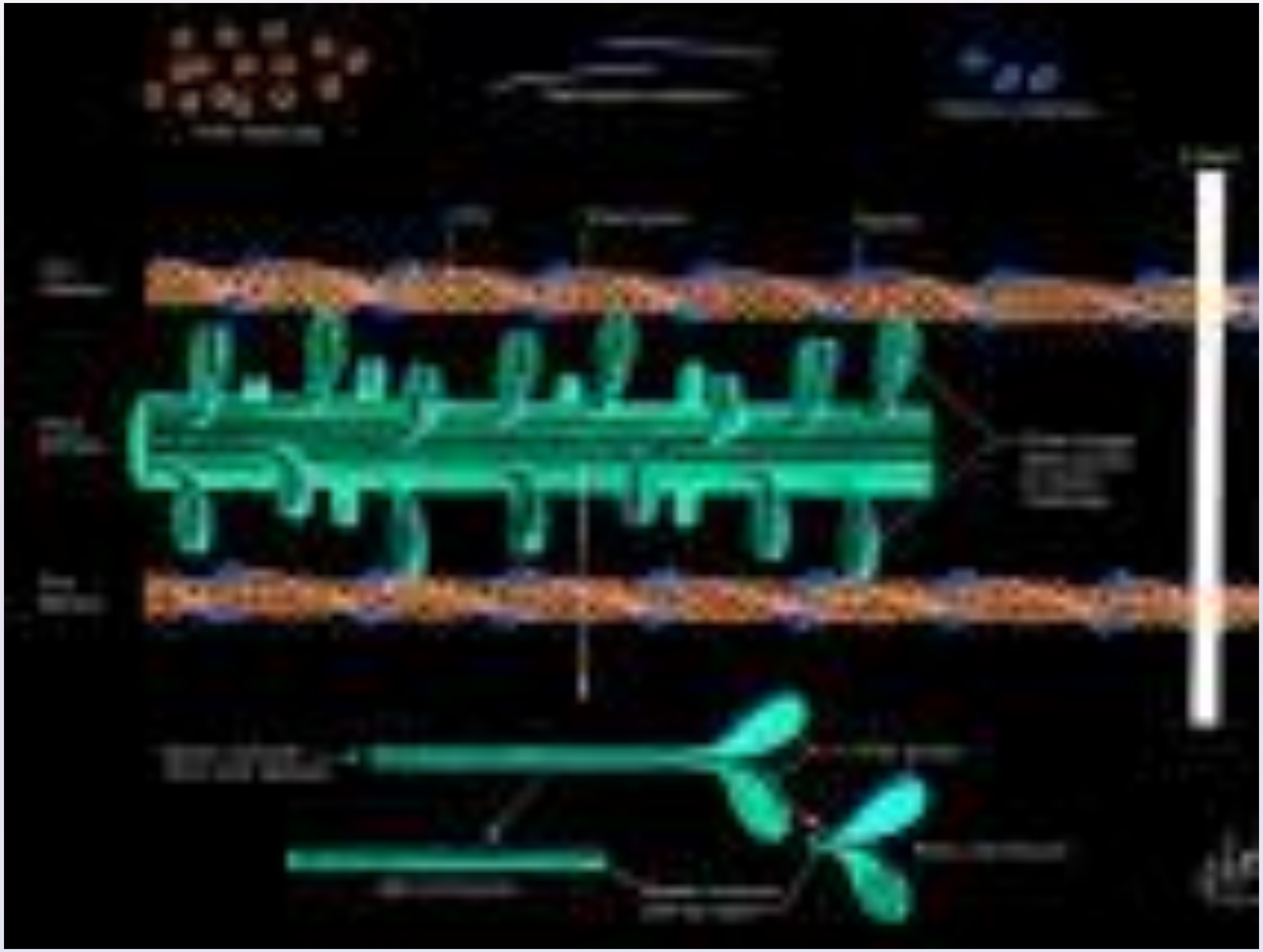
- Muscle fiber:
  - Cylindrical cell:
    - From mm to several cm
  - Myofibrils actin, myosin and titin
    - Energy conversion from chemical to mechanical Ca++
  - Functioning characteristics
    - Force-velocity e Force-length

Contractile mechanism

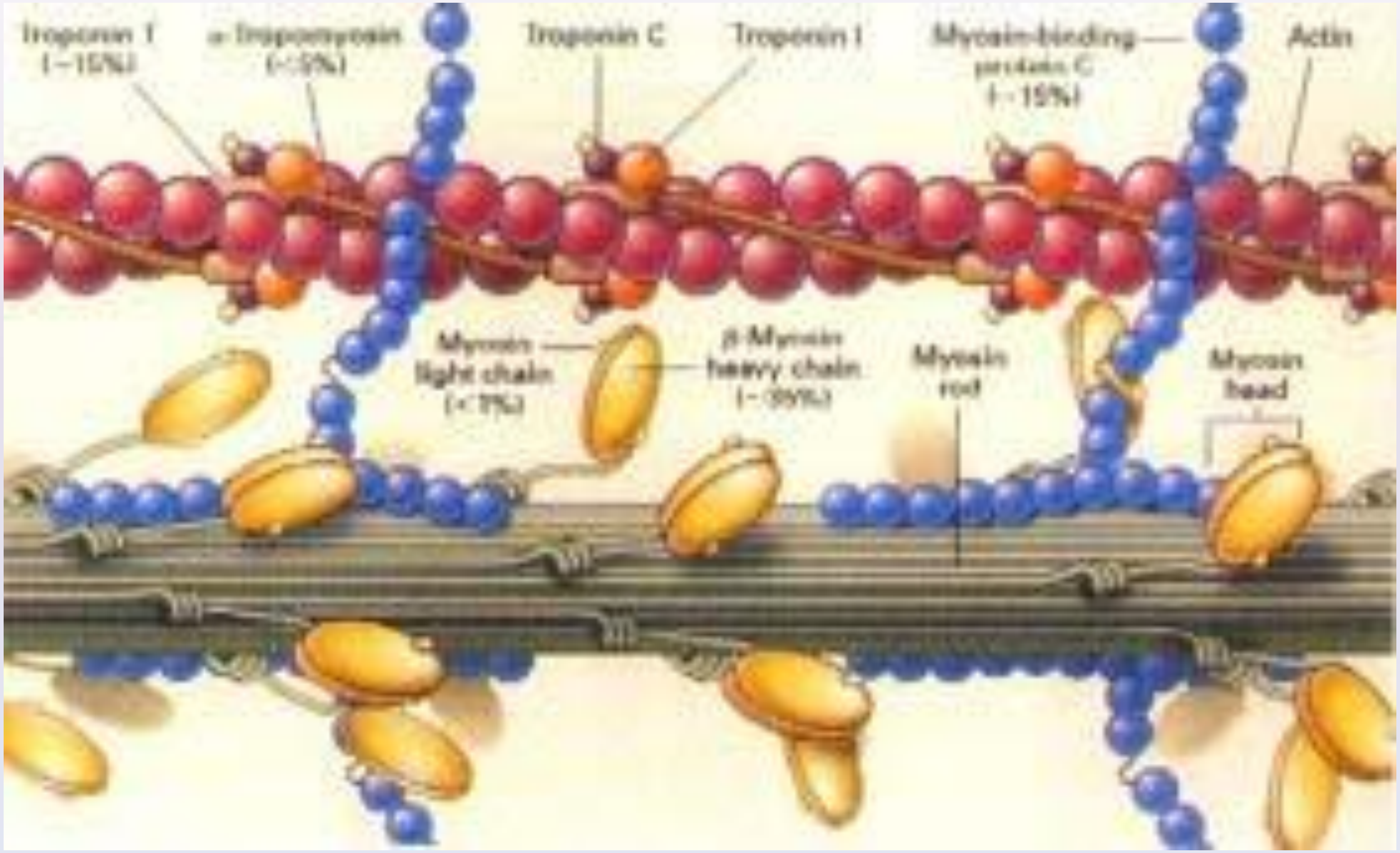
- Transducer:
  - Electrical pulse in the motor plate
  - Chemical diffusion Ca++
  - Linear displacement



Displacement of actin e myosin



Myofibrils


Troponin T
(~15%)
α-Tropomyosin
(<5%)
Troponin C
Troponin I
Myosin-binding
protein C
(~15%)
Actin
Myosin
light chain
(<1%)
β-Myosin
heavy chain
(~35%)
Myosin
rod
Myosin
head

Motor unit

- Myofibers innervated by the same moto-neuron
- Three MU types: I SO, IIB FG and IIA FOG
- Innervation ratio: nº of myofibers x moto-neuron
- Determines the force generation accuracy:
  - Eye muscles: 1:1 muscle/nerve
  - Harmstrings: 300:1 muscle/nerve

Fiber types

- Slow Oxidative (SO) ⇔ Type I
  - Slow twitch oxidative
  - Aerobic
  - Red (highly capilarized)
- Fast-twitch Oxidative (FOG) ⇔ Type IIA
  - Anaerobic with certain resistance
  - Intermediate capilarized (red)
- Fast-twitch Glycolitic (FG) ⇔ Type IIB
  - Anaerobic
  - White

Myofiber types+motor units

- Slow-twitch (S)
  - Slow
- Fast-twitch (F)
  - Fatigue-resistant (FR)
  - Fatigue-intermediate (Fint)
  - Fatigable (FF)

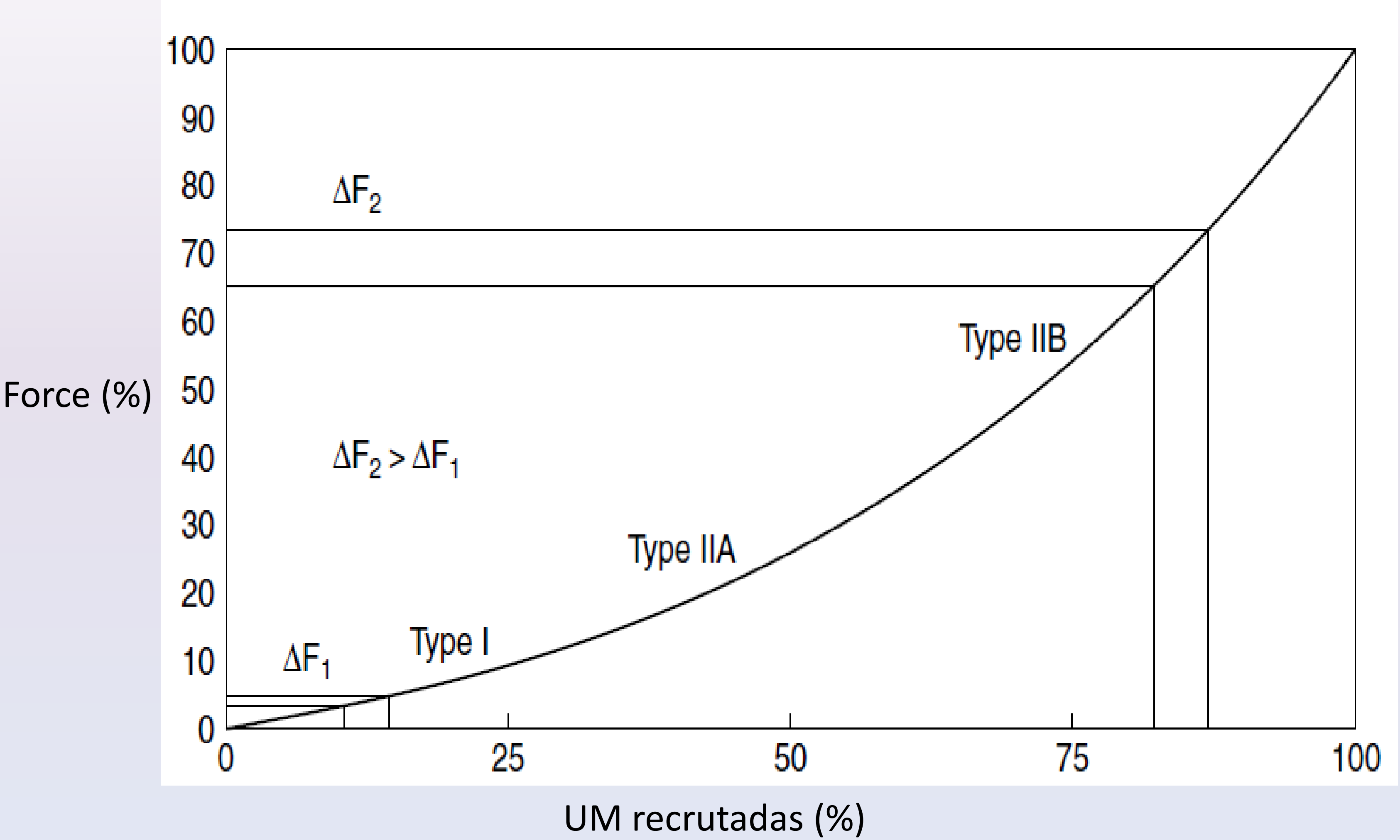
Motor unit

- Muscle contraction: initiated by depolarization of the motor-neuron that innervates the muscle in the motor plate (motor end-plate).
    - excitable muscle tissue
    - changes length generating strength when excited
- Active displacement contraction (energy consumption) of myofilaments
- Each fiber can generate around 0.3 N.

Motor unit

- *Size contraction principle* (Henneman 1957).
  - First the smaller UM ae recruites (SO) and to increase force larger UM are recruited (FG, FOG)
- Rotation of active MUs
  - After some time of stimulation the MU goes off
  - How is rotation controlled? (refractory period?)
- Mechanism to delay fatigue…
- Mechanism to increase force:
  - Increase activation frequency
  - Increase the number of active MUs

Size contraction principle



Descriptive conclusions

- Contraction: electro-chemical phenomenon
  - Bridges actin-myosin (*cross-bridges*)
  - Difussion of Ca++
  - Delay in the synaptic junction
- Recruitment mechanisms
  - Order
  - Frequency

Functioning principles

- Relation Force-velocity (Hill, 1938)
  - Output force of a tetanized sarcomere depends of the contraction velocity v:

$$(v+b)(F+a)=b(F_0+a)$$

  - Constants: a, b e F_0: tetanized muscle force
  - Rate of work : constant
    - Energy conversion rate of the chemical reaction

Functioning principles

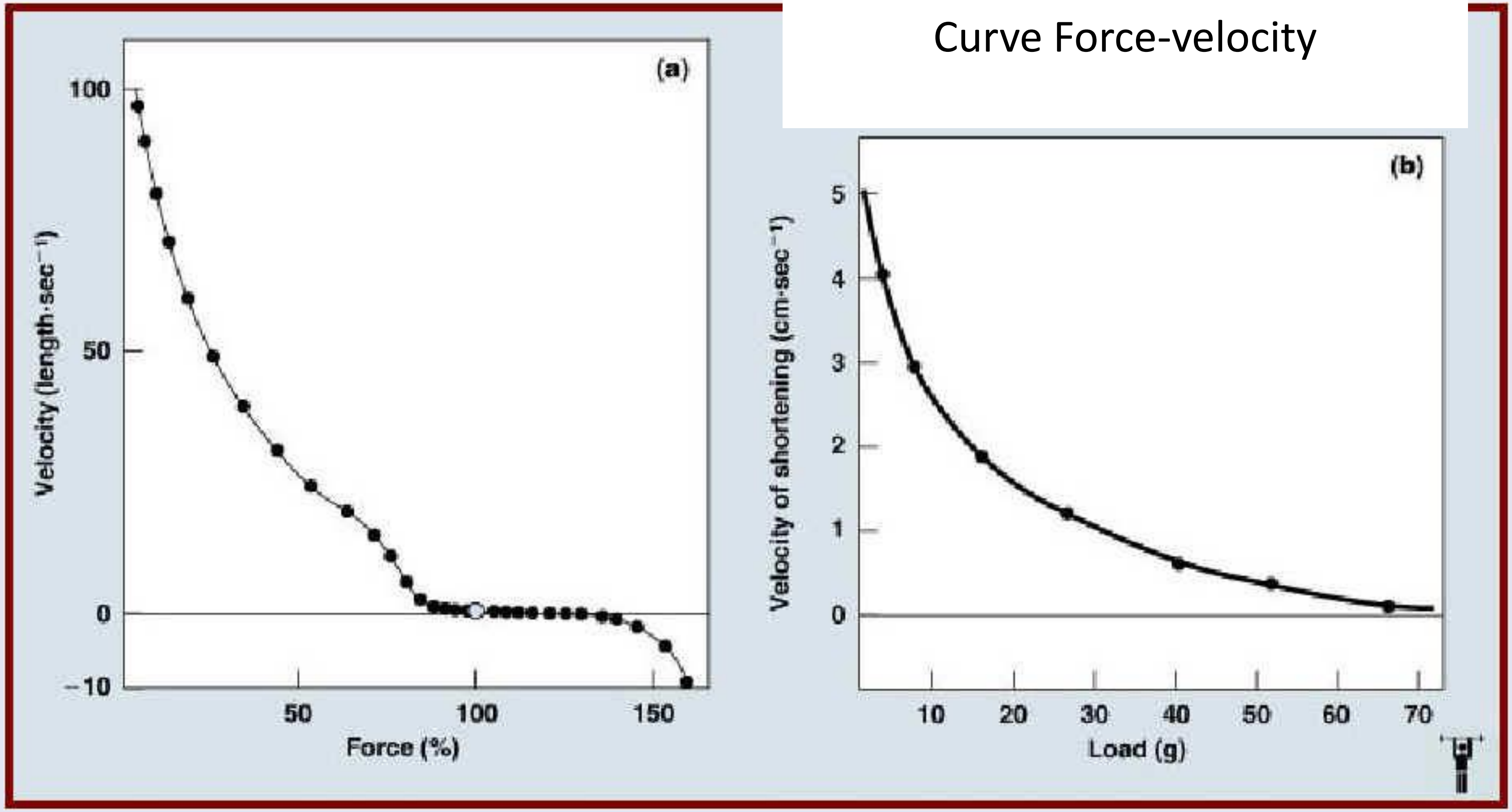
...or:

$$F= F_0 (1-(v/v_0))/(1+c(v/F_0))$$

$c=F_0/a$ e v_0= bc max contraction velocity

- Values:
  - Resting length: l_r
  - Fast fibers $c=0.1$ e $v_0=8\ l_r$ per second
  - Slow fibers $c=1$ e $v_0=2\ l_r$ per second
  - Depemdency of F_0

Curve Force-velocity



Curve Force-velocity

Functioning principles

- Relation Force-length
  - N of overlapped actin-myosin cross-bridges α :
  - F_0 depends of sarcomere length:

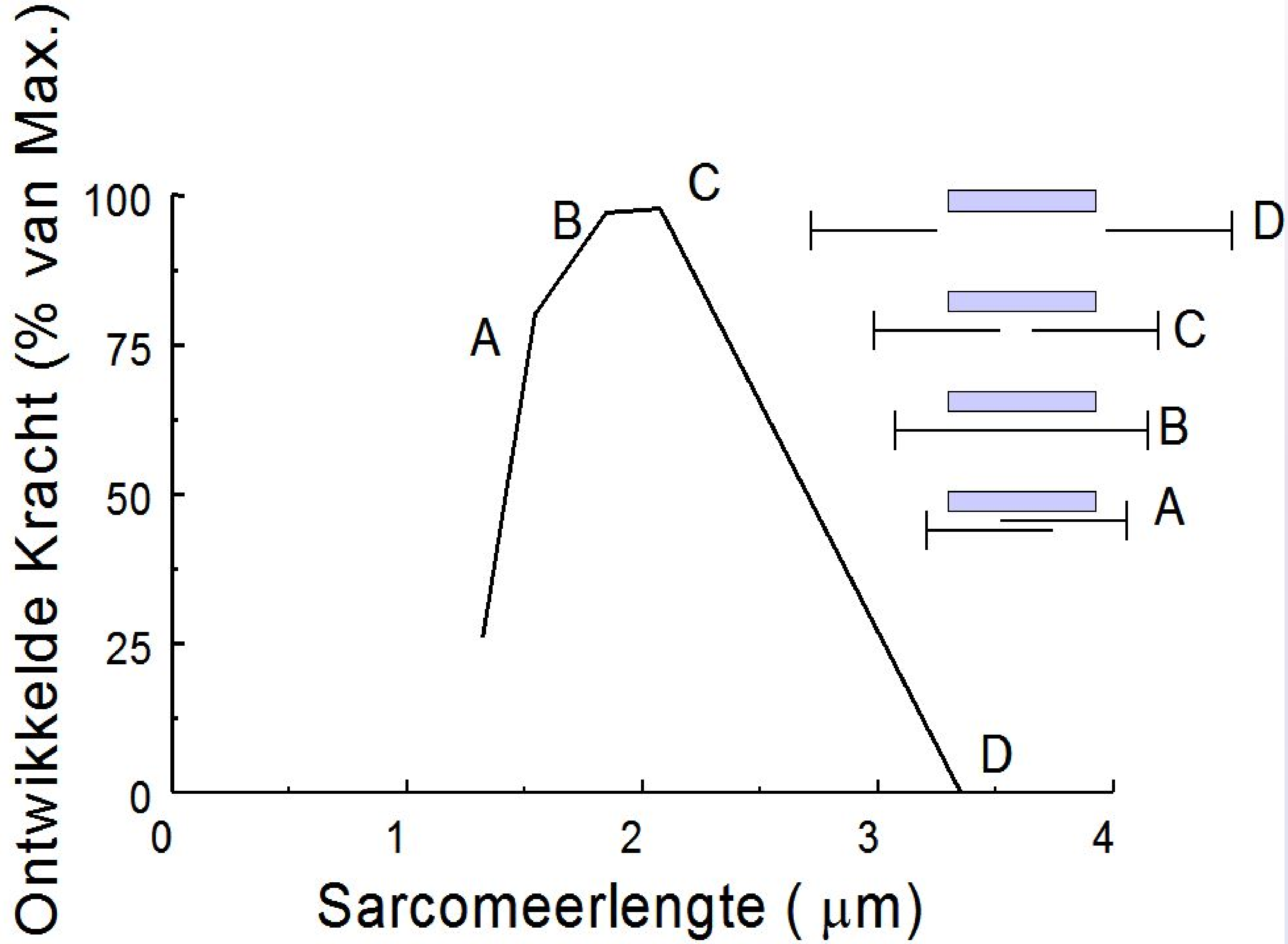
$$F_0 = F_{max}\, f(l)$$

F_{max} maximal force at optimal sarcomere length -l-

Values: 10-100 N/cm^2

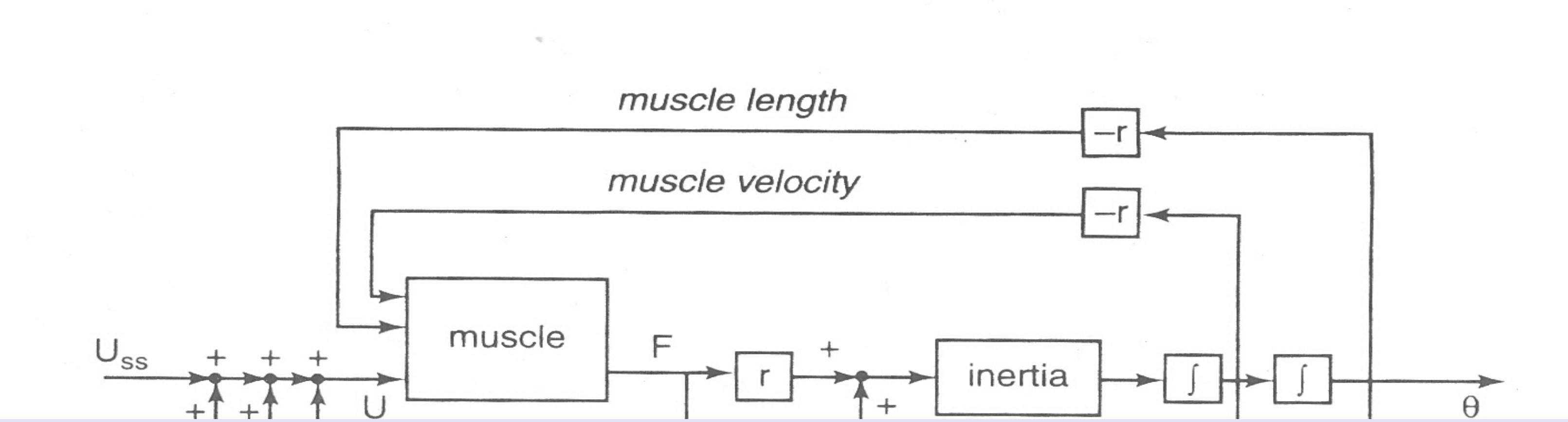
$$F = F_{max}\, f(l)(1-(v/v_0))/(1+c(v/F_0))$$

  - This is valid for a tetanized fiber
  - It is assumed that length and contraction velocity are independent...


Ontwikkelde Kracht (% van Max.)
100
75
50
25
0
0
1
2
3
4
Sarcomeerlengte (μm)
A
B
C
D
D
C
B
A

Muscle models

- Compromise: complexity vs detail
- Relation neural ativity=>joint trajectoryr
- Description: Force-length and velocity
- Two approaches

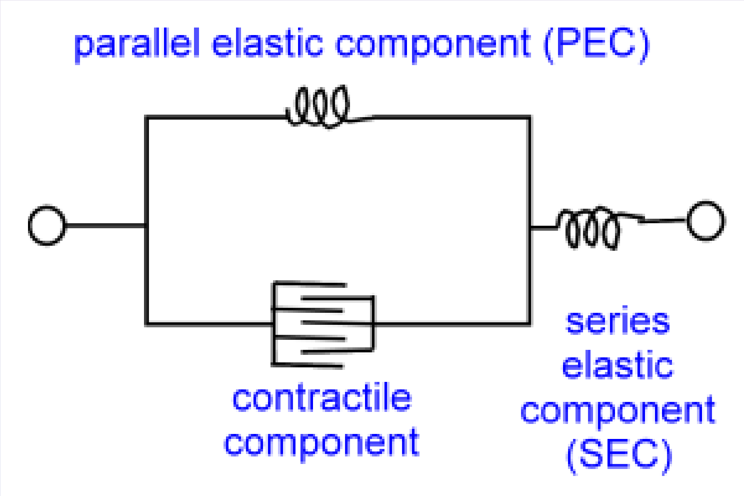


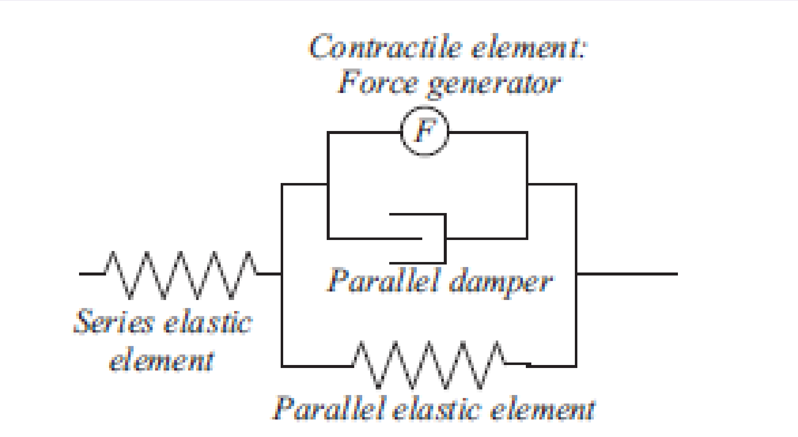
Muscle models

- Sarcomere poperties:
  - Contraction dynamics:
    - Tension-Length
    - Tension-velocity
  - Activation dynamics:
    - Input: neural signal
    - Output: muscle activation
- Two types of models:
  - Macroscopic (Hill)
  - Microscopic (Huxley)

Hill model

- Sarcomere (CE)
- Tendon (SE)
- Connective tissues: epimysium,... (PE)





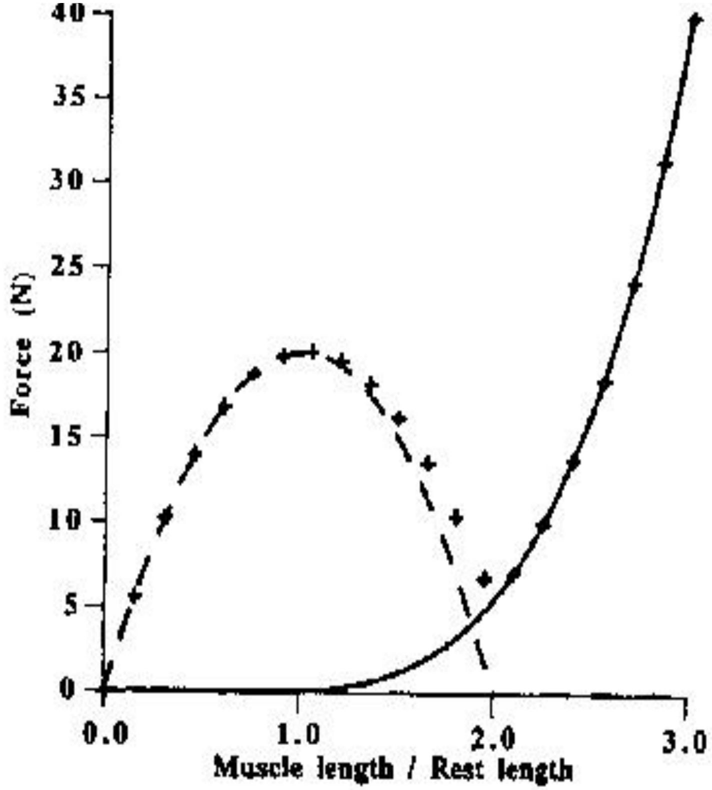
Hill model

- $F_{mus}=F_{SE}+F_{CE}$
- $F_{SE}=F_{CE}/\cos(\varphi)$
- $F_{CE}= F_{max}\, q(t)f(l)g(v)$
- q(t) is a function of the activation state
  φ represents the pennation angle
  g(v) is the tension-velocity relation
  (atention $g(v)=(1-(v/v_0))/(1+c(v/F_0))$ is valid only for concentric contractions)

Tension-length curve

Tension-Length:

Active and passive



- Two contributions:
  - Passive (PE)
  - Active (CE)
  - Passive tension depends on velocity: viscoelasticity
- Polynomic and exponential relation

Activation function

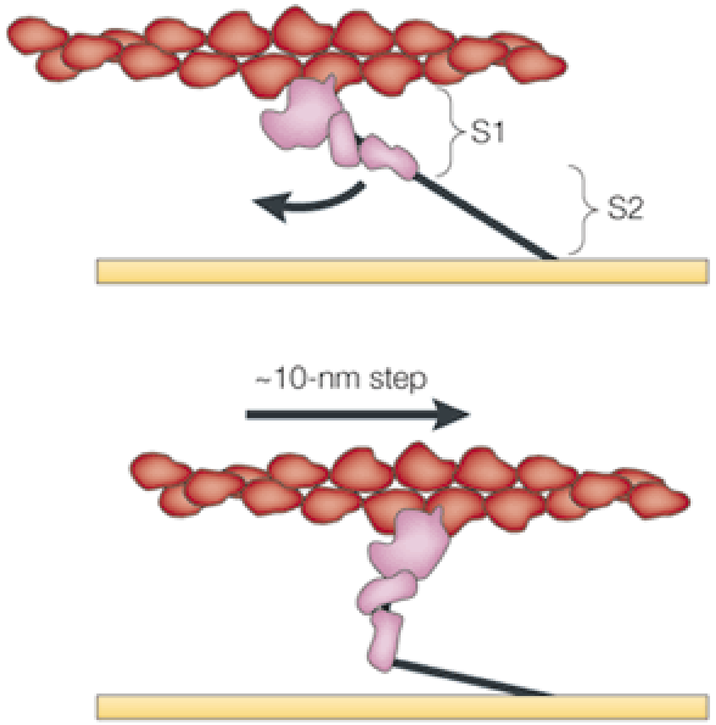
- Neural input u(t) => muscle activity q(t)
- Winters&Stark model (1985):
  - Two differential equations (order 1):
    1. Excitation dynamics:
       - 30ms
    2. Ca++ concentration:
       - Ativation: 10 ms
       - Deativation: 50 ms
    3. Concentration of Ca++ Linear relation with the output force

Reflections of the Hill models

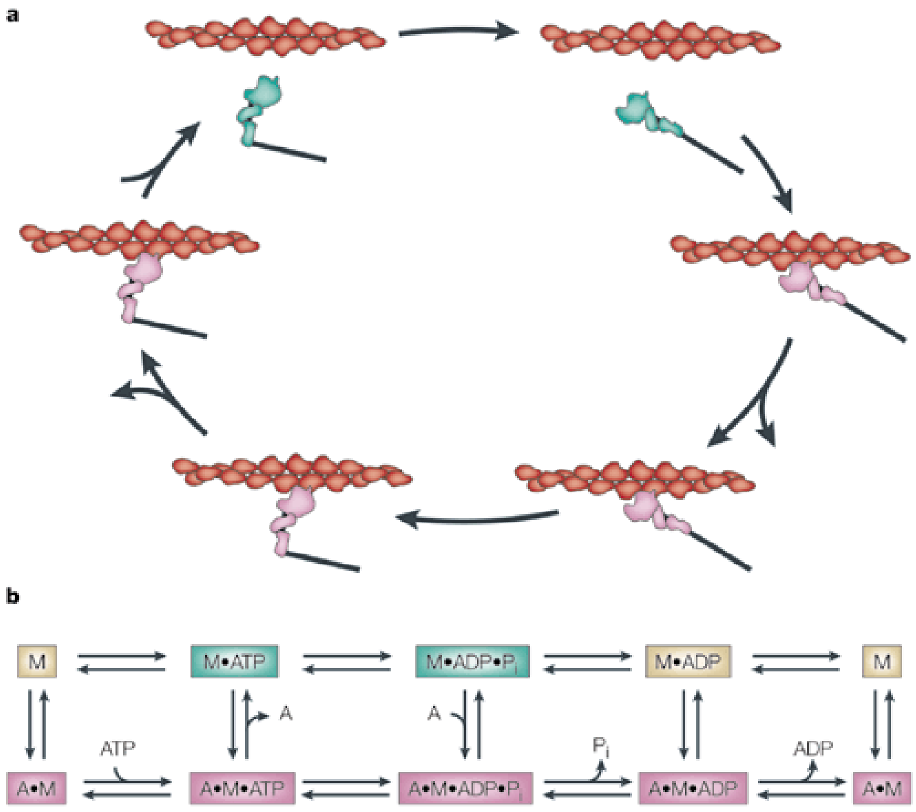
- Independency of the length and velocity
- Unknown paramters:
  - Measured for muscle in vitro
  - Different for a muscle in vivo
- Non constant parameters
- Hill models: experimentals (curve fitting)
- Tension-Length: negative slope=negative stiffness

Cross-bridge models

- Molecular level: Contractile element
  - Two states:
    - Attach f(x)
    - Detach g(x)
    - Depend of the x distance within a range
  - Attachment probability depends on the distance
  - The total force results of the integration of the cross-bridges forces.
    - It is needed to know the rigidity

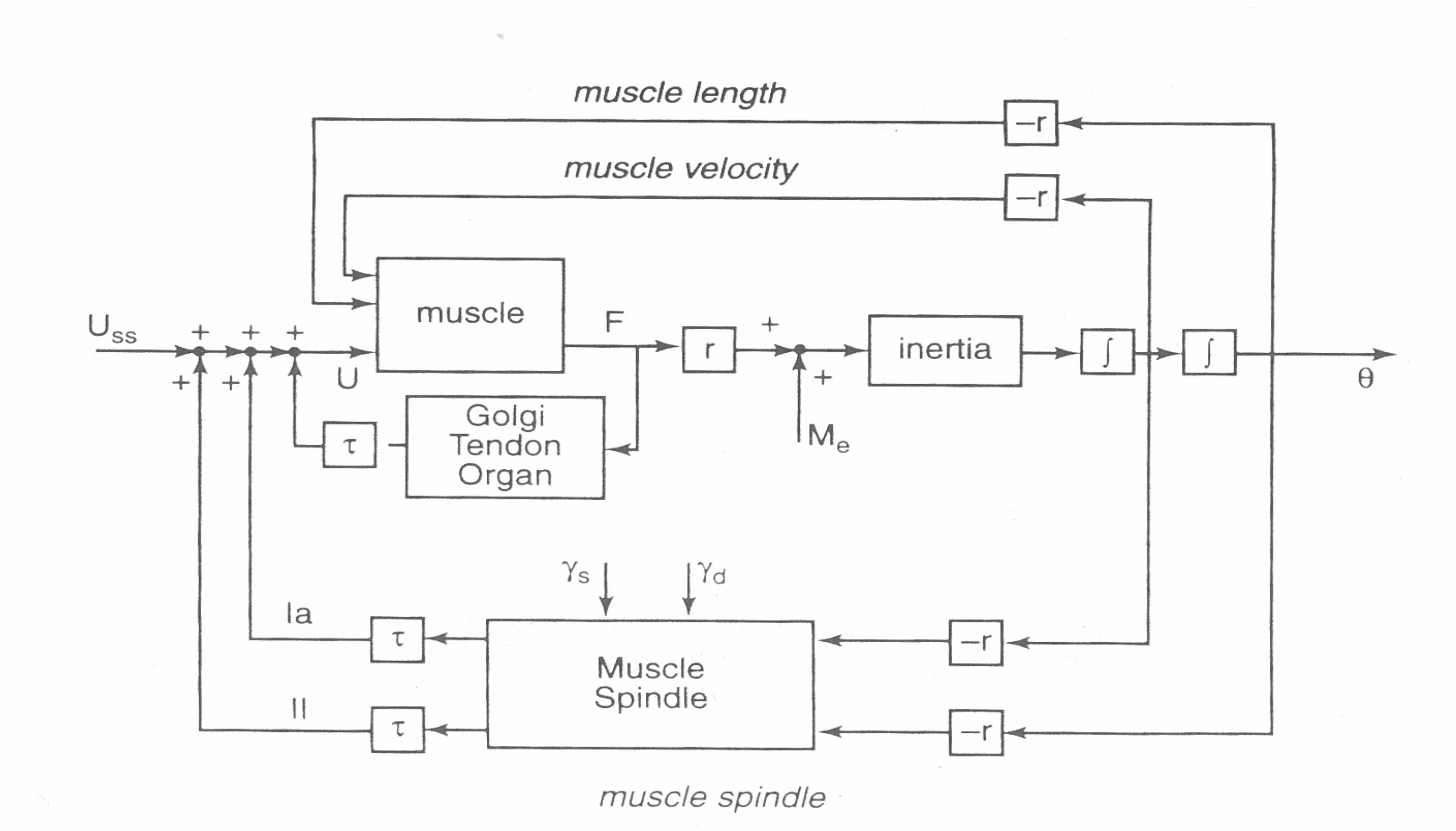


Nature Reviews | Molecular Cell Biology

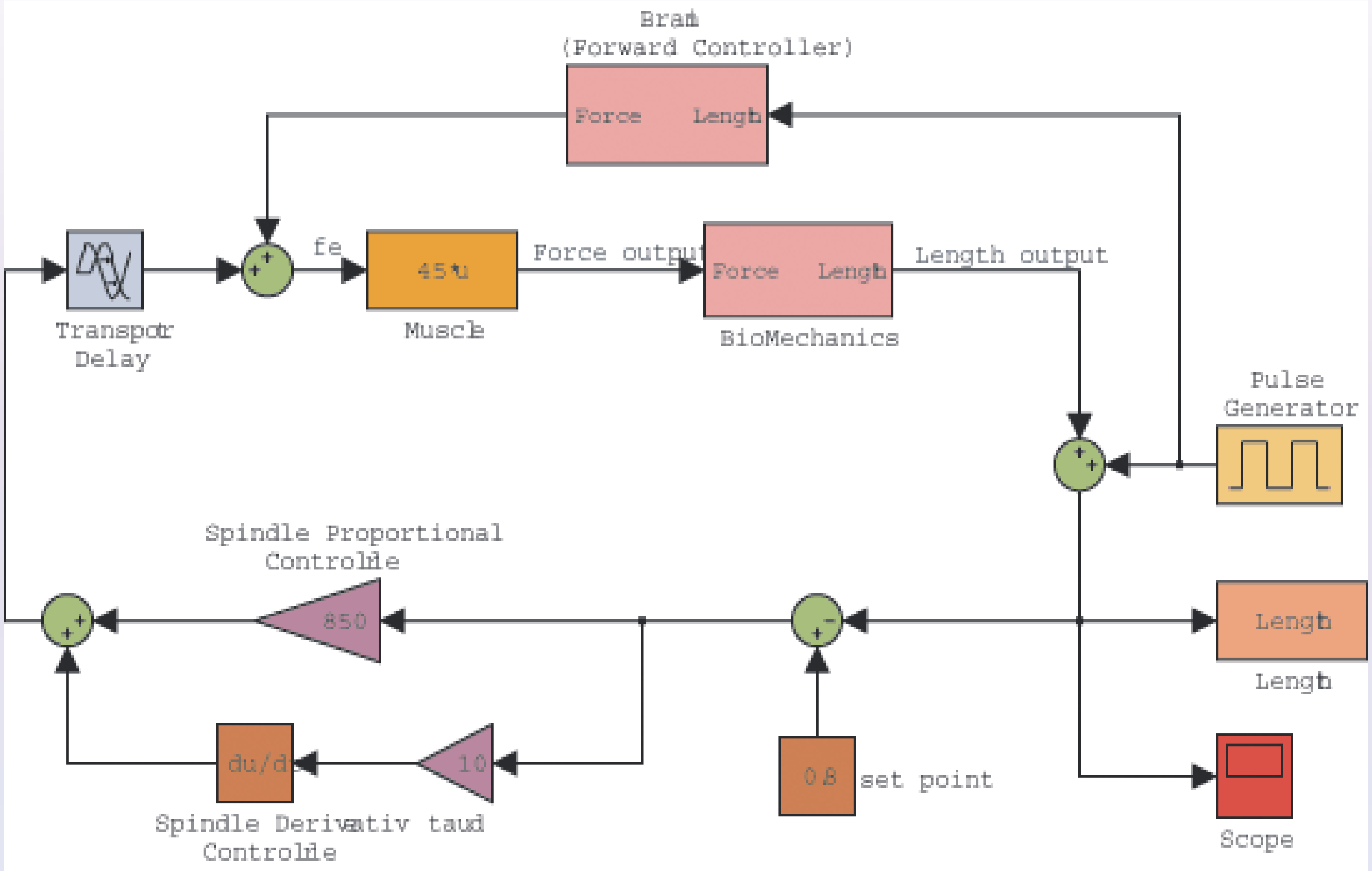


Nature Reviews | Molecular Cell Biology

Model: muscle and miotatic reflex



Van der Helm FCT, Rozendaal LA (2000). muscleskeletal systems with intrinsic and proprioceptive feedback. In: Winters JM, Crago P (Eds), Neural control of posture and movement, Springer Verlag, NY, 164-174


Brain
(Forward Controller)
Force
Length
fe
45*u
Muscle
Force output
Force
Length
BioMechanics
Length output
Transport Delay
Pulse Generator
Spindle Proportional Controller
850
Length
Length
10
du/dt
Spindle Derivative Controller
tau d
0.8
set point
Scope

Contents

1. Introduction: Justification and goals

2. Biological actuators
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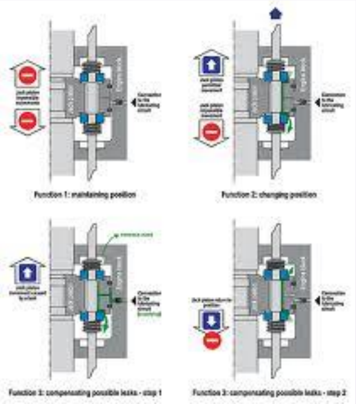
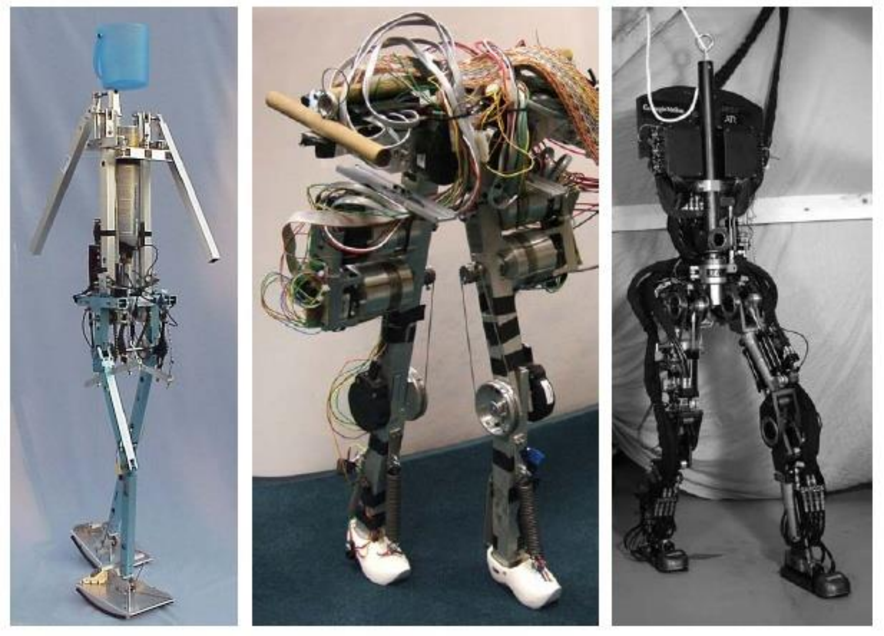
Robotic actuators

- Hydraulic
- Pneumatic
- Electromagnetic
- Other





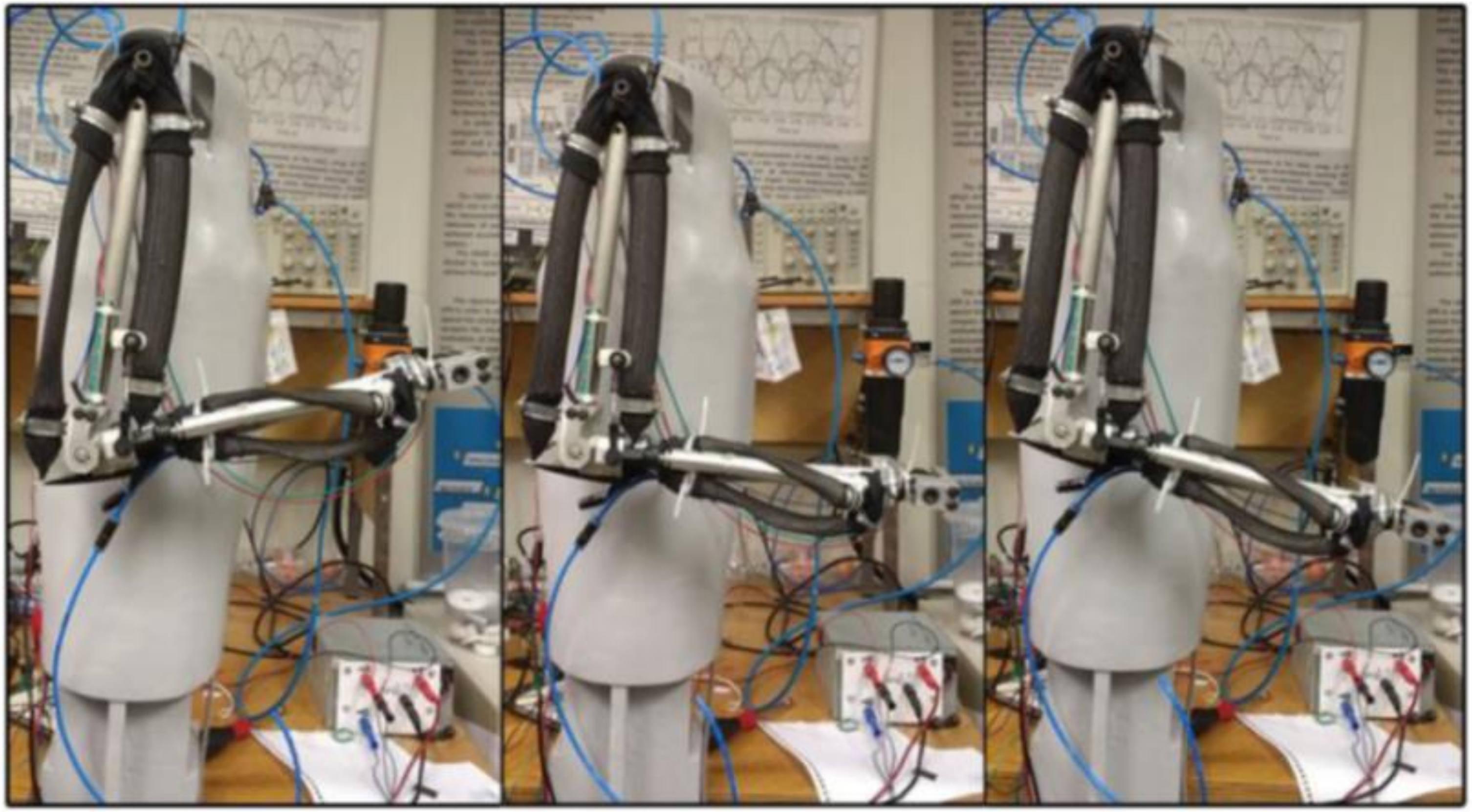
Hydraulic

- Advantages:
  - High forces
  - High weight-power rate
  - Control:
    - Solenoid (on-off)
    - Servo valve (proportional)
- Disadvantages
  - Need to pump liquid for power supply
  - High cost of fast servo valves
  - Problems of leakages and maintenance

Pneumatic

- Point-to-point motion
- Simple control
  - Non-linear behavior difficult to model
- Low cost
- Low energy efficiency
- Pneumatic manipulators servo-controlled with feedback and proportional control
- Biomimetism: pneumatic muscles

Pneumatic muscles

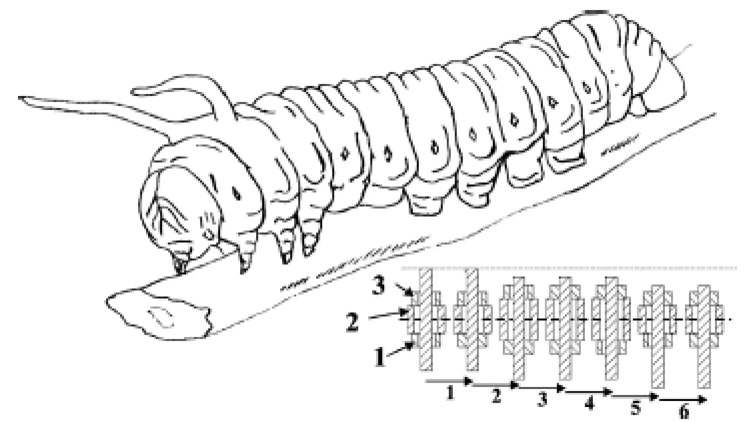


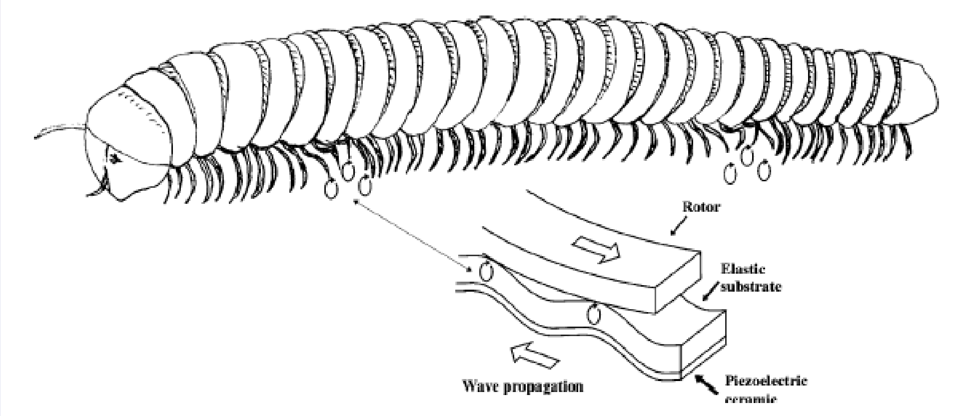
Electromagnetic (electric motors)

- Step motors:
  - Open-loop
- DC motors:
  - High weight and size
- Brushless motors:
  - Higher control complexity
  - Rotational and linear actuators

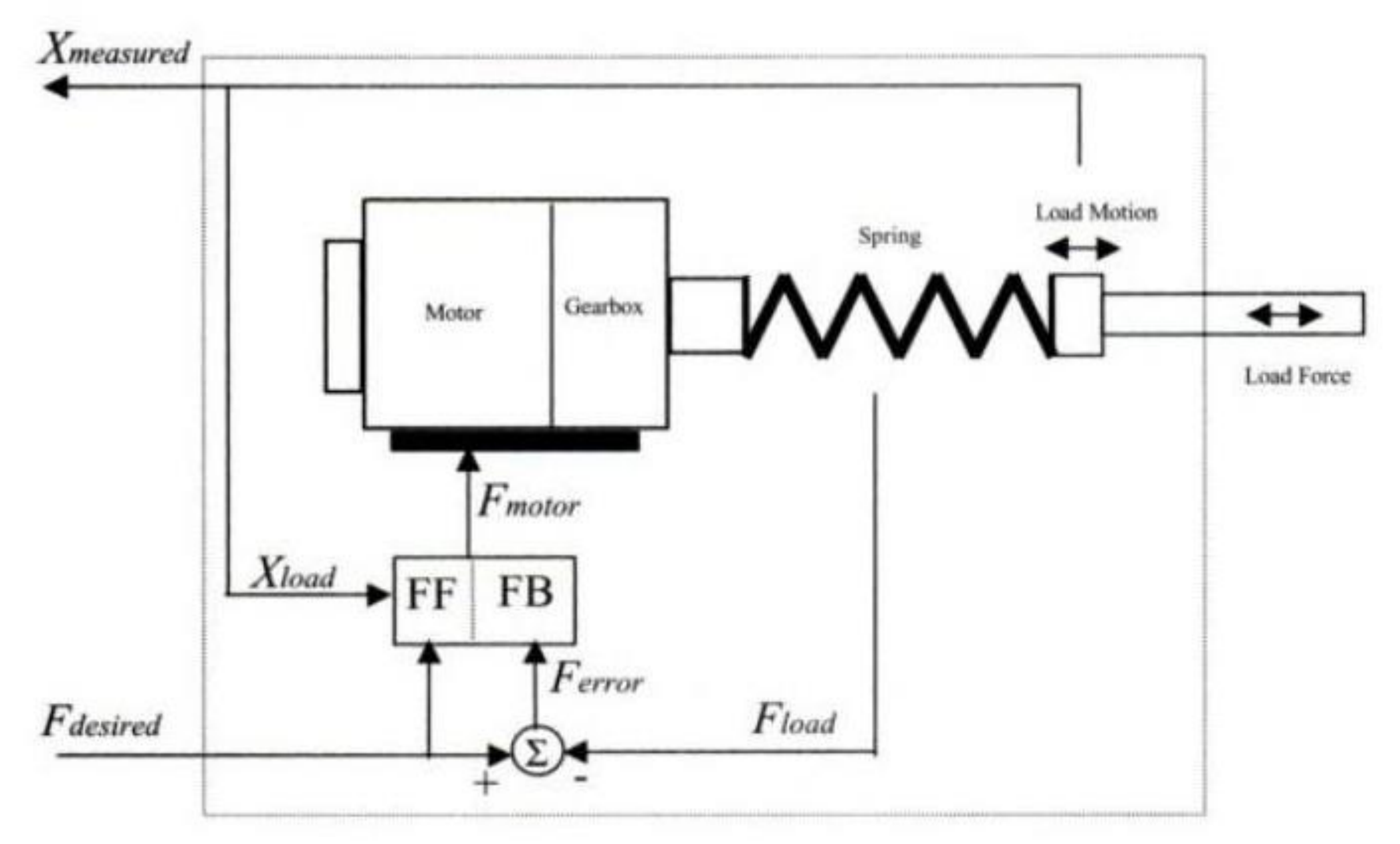
Other types

- Electroactive polymers (EPAM)
- *Shape memory alloys*
- Piezoelectrics
- Ultrasonic motors

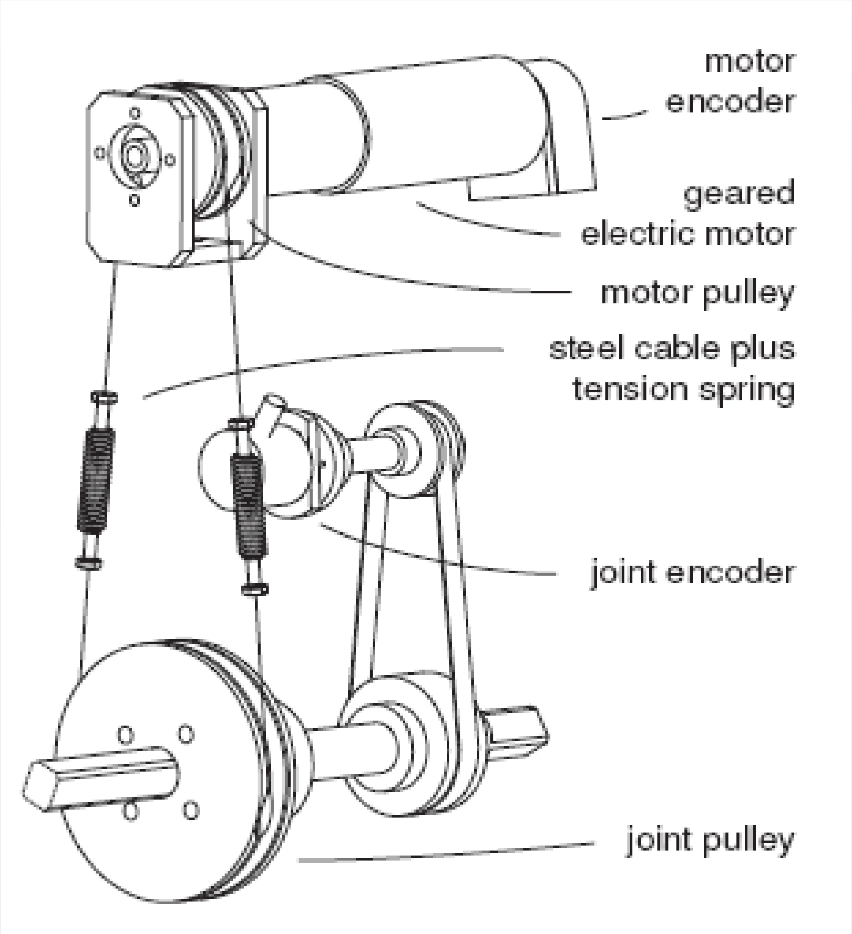




Artificial actuators: Series Elastic Actuators



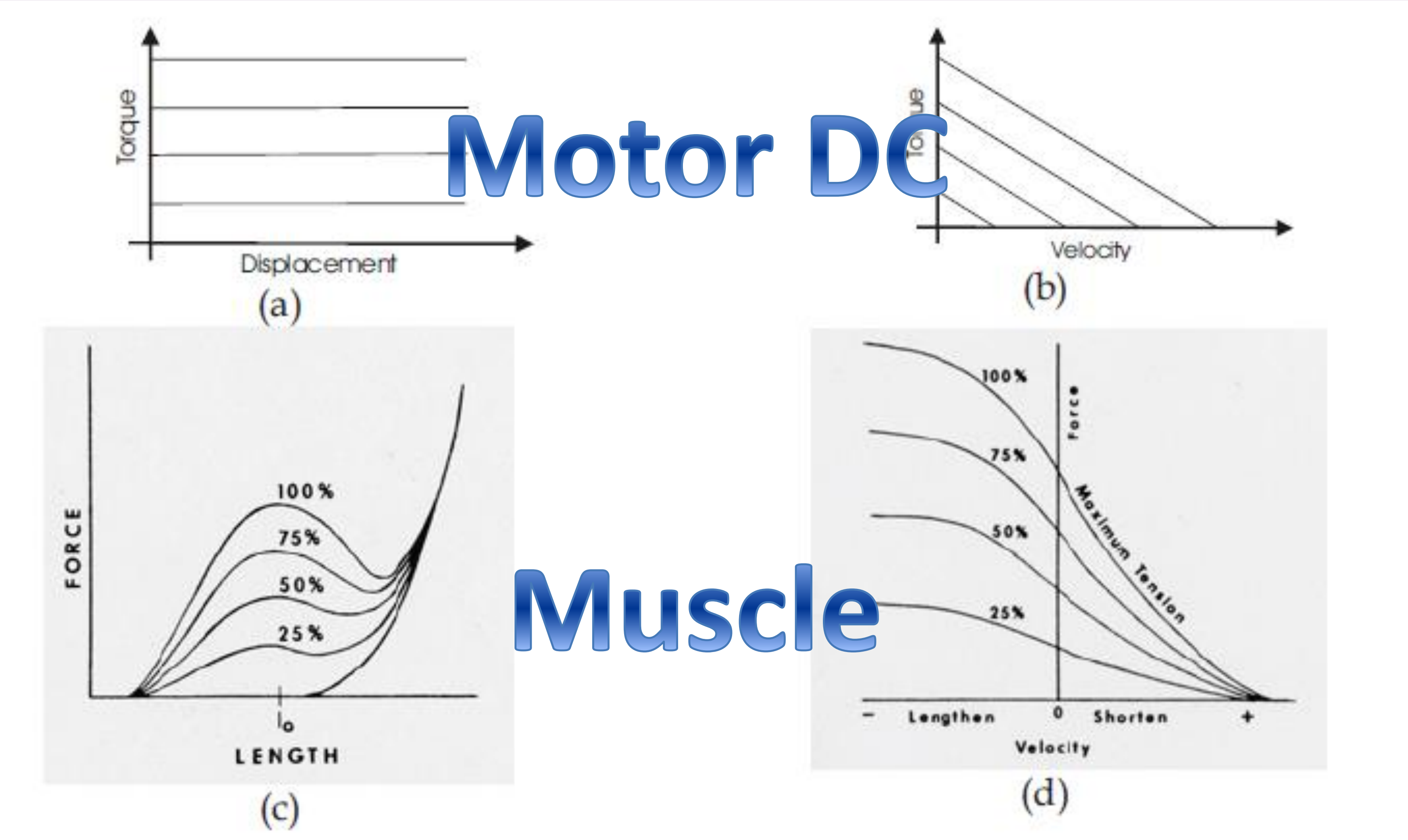
Elastic-series actuators



Comparison of actuators

- Definition of compatible metrics:
  - Output power:
    - Actuator mass
    - Actuator volume
    - Efficiency
  - Other measures*: stress, strain, strain rate, cycle life*, mechanical impedance
  - Backdrivability

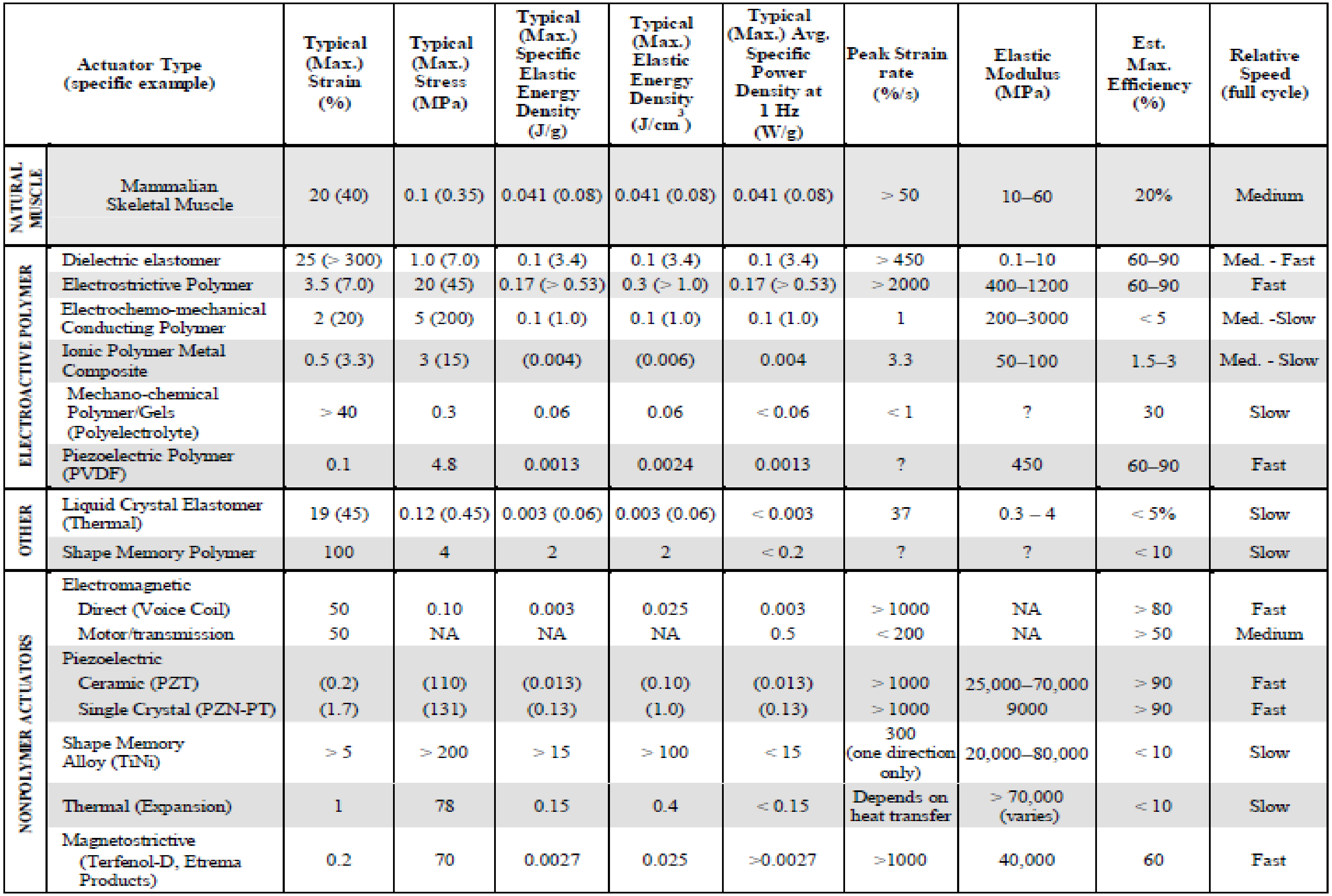
Comparison example



Motor DC

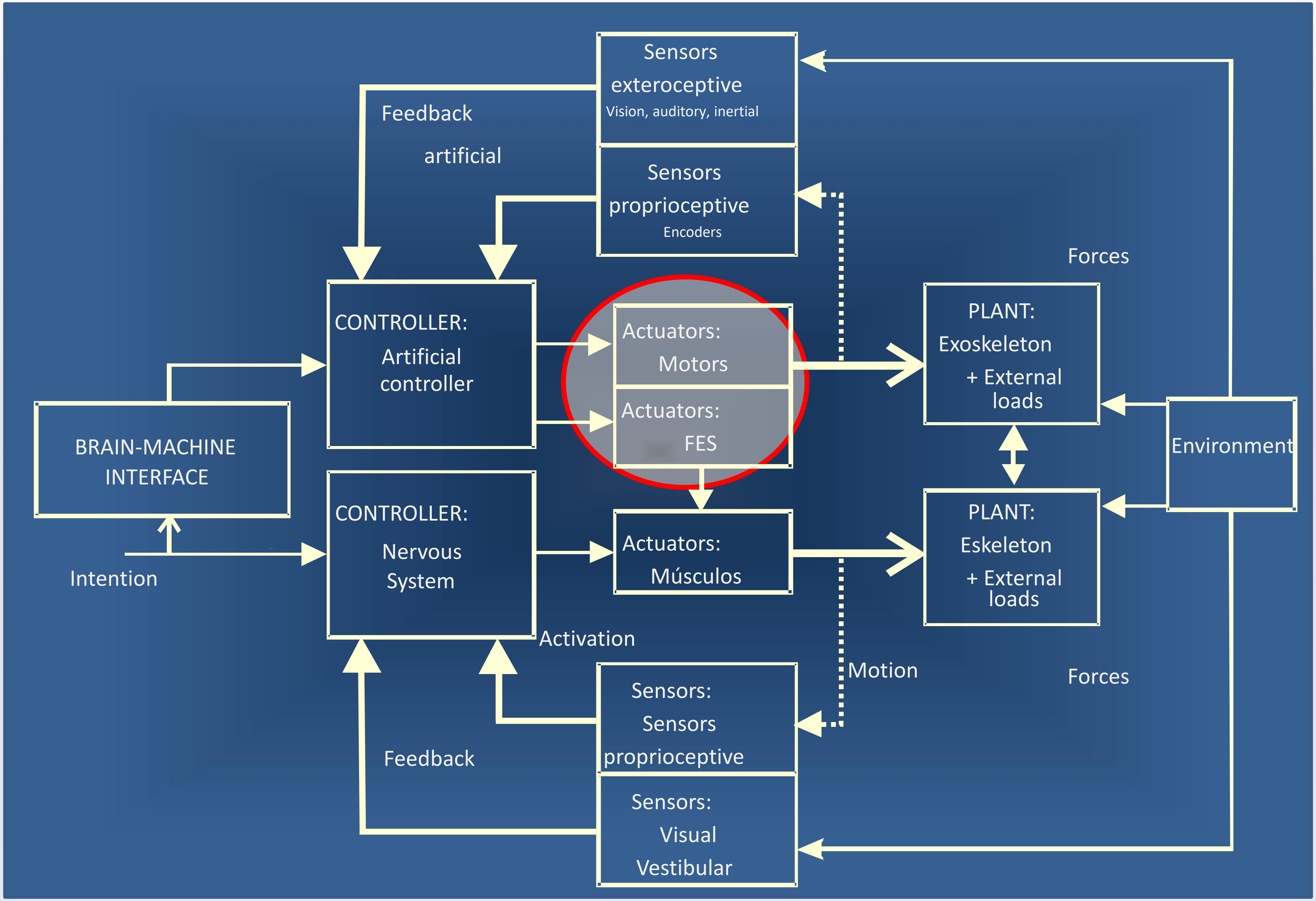
Muscle

Actuator comparison



	Actuator Type (specific example)	Typical (Max.) Strain (%)	Typical (Max.) Stress (MPa)	Typical (Max.) Specific Elastic Energy Density (J/g)	Typical (Max.) Elastic Energy Density (J/cm^3)	Typical (Max.) Avg. Specific Power Density at 1 Hz (W/g)	Peak Strain rate (%/s)	Elastic Modulus (MPa)	Est. Max. Efficiency (%)	Relative Speed (full cycle)
NATURAL MUSCLE	Mammalian Skeletal Muscle	20 (40)	0.1 (0.35)	0.041 (0.08)	0.041 (0.08)	0.041 (0.08)	> 50	10–60	20%	Medium
ELECTROACTIVE POLYMER	Dielectric elastomer	25 (> 300)	1.0 (7.0)	0.1 (3.4)	0.1 (3.4)	0.1 (3.4)	> 450	0.1–10	60–90	Med. - Fast
	Electrostrictive Polymer	3.5 (7.0)	20 (45)	0.17 (> 0.53)	0.3 (> 1.0)	0.17 (> 0.53)	> 2000	400–1200	60–90	Fast
	Electrochemo-mechanical Conducting Polymer	2 (20)	5 (200)	0.1 (1.0)	0.1 (1.0)	0.1 (1.0)	1	200–3000	< 5	Med. -Slow
	Ionic Polymer Metal Composite	0.5 (3.3)	3 (15)	(0.004)	(0.006)	0.004	3.3	50–100	1.5–3	Med. - Slow
	Mechano-chemical Polymer/Gels (Polyelectrolyte)	> 40	0.3	0.06	0.06	< 0.06	< 1	?	30	Slow
	Piezoelectric Polymer (PVDF)	0.1	4.8	0.0013	0.0024	0.0013	?	450	60–90	Fast
OTHER	Liquid Crystal Elastomer (Thermal)	19 (45)	0.12 (0.45)	0.003 (0.06)	0.003 (0.06)	< 0.003	37	0.3 – 4	< 5%	Slow
	Shape Memory Polymer	100	4	2	2	< 0.2	?	?	< 10	Slow
NONPOLYMER ACTUATORS	Electromagnetic									
	Direct (Voice Coil)	50	0.10	0.003	0.025	0.003	> 1000	NA	> 80	Fast
	Motor/transmission	50	NA	NA	NA	0.5	< 200	NA	> 50	Medium
	Piezoelectric									
	Ceramic (PZT)	(0.2)	(110)	(0.013)	(0.10)	(0.013)	> 1000	25,000–70,000	> 90	Fast
	Single Crystal (PZN-PT)	(1.7)	(131)	(0.13)	(1.0)	(0.13)	> 1000	9000	> 90	Fast
	Shape Memory Alloy (TiNi)	> 5	> 200	> 15	> 100	< 15	300 (one direction only)	20,000–80,000	< 10	Slow
	Thermal (Expansion)	1	78	0.15	0.4	< 0.15	Depends on heat transfer	> 70,000 (varies)	< 10	Slow
	Magnetostrictive (Terfenol-D, Etrema Products)	0.2	70	0.0027	0.025	>0.0027	>1000	40,000	60	Fast

Motor compensation



Sensors exteroceptive
Vision, auditory, inertial

Sensors proprioceptive
Encoders

Feedback artificial

CONTROLLER: Artificial controller

Actuators: Motors

Actuators: FES

PLANT: Exoskeleton + External loads

Forces

BRAIN-MACHINE INTERFACE

Intention

Environment

CONTROLLER: Nervous System

Actuators: Músculos

PLANT: Eskeleton + External loads

Activation

Motion

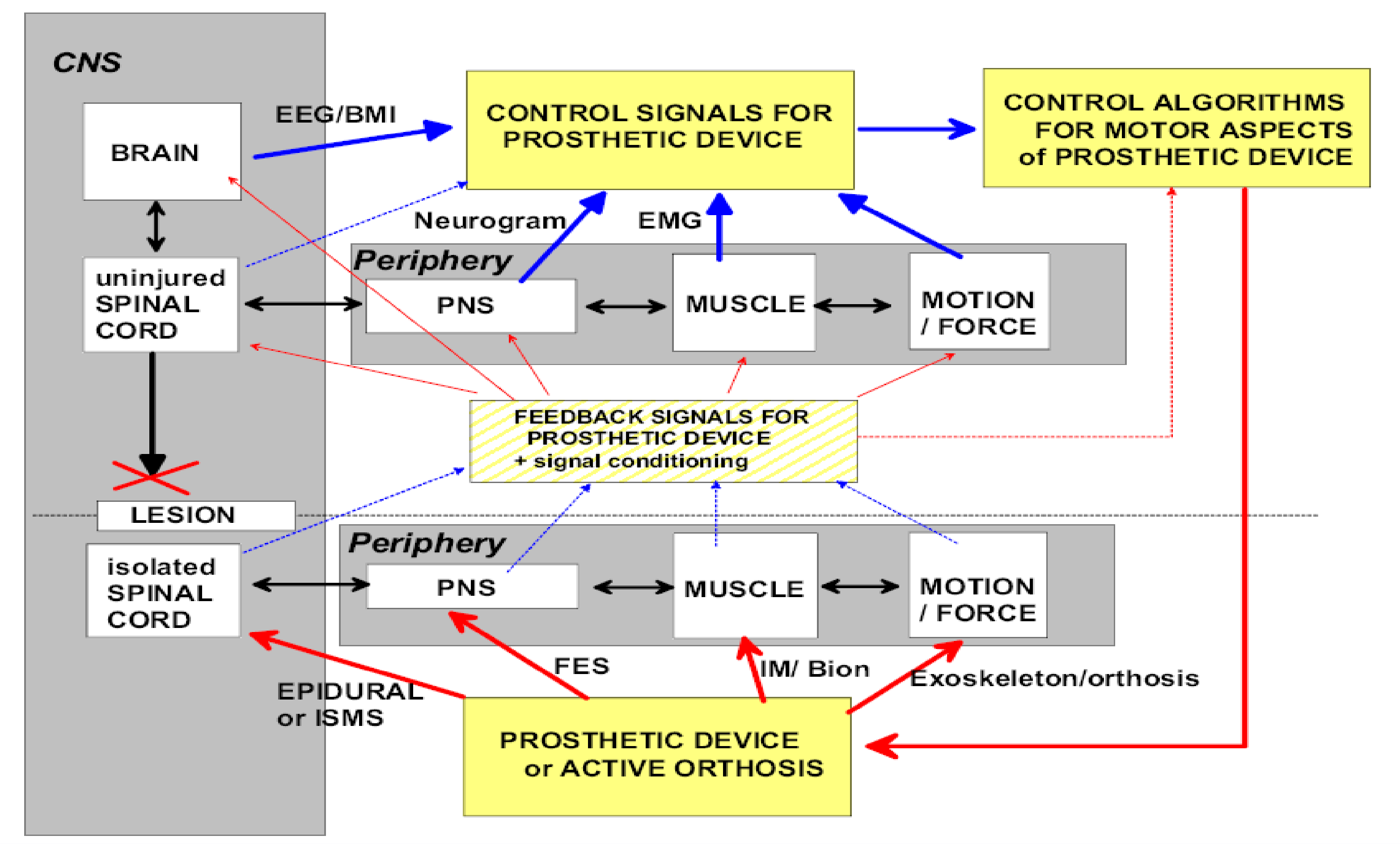
Forces

Feedback

Sensors: Sensors proprioceptive

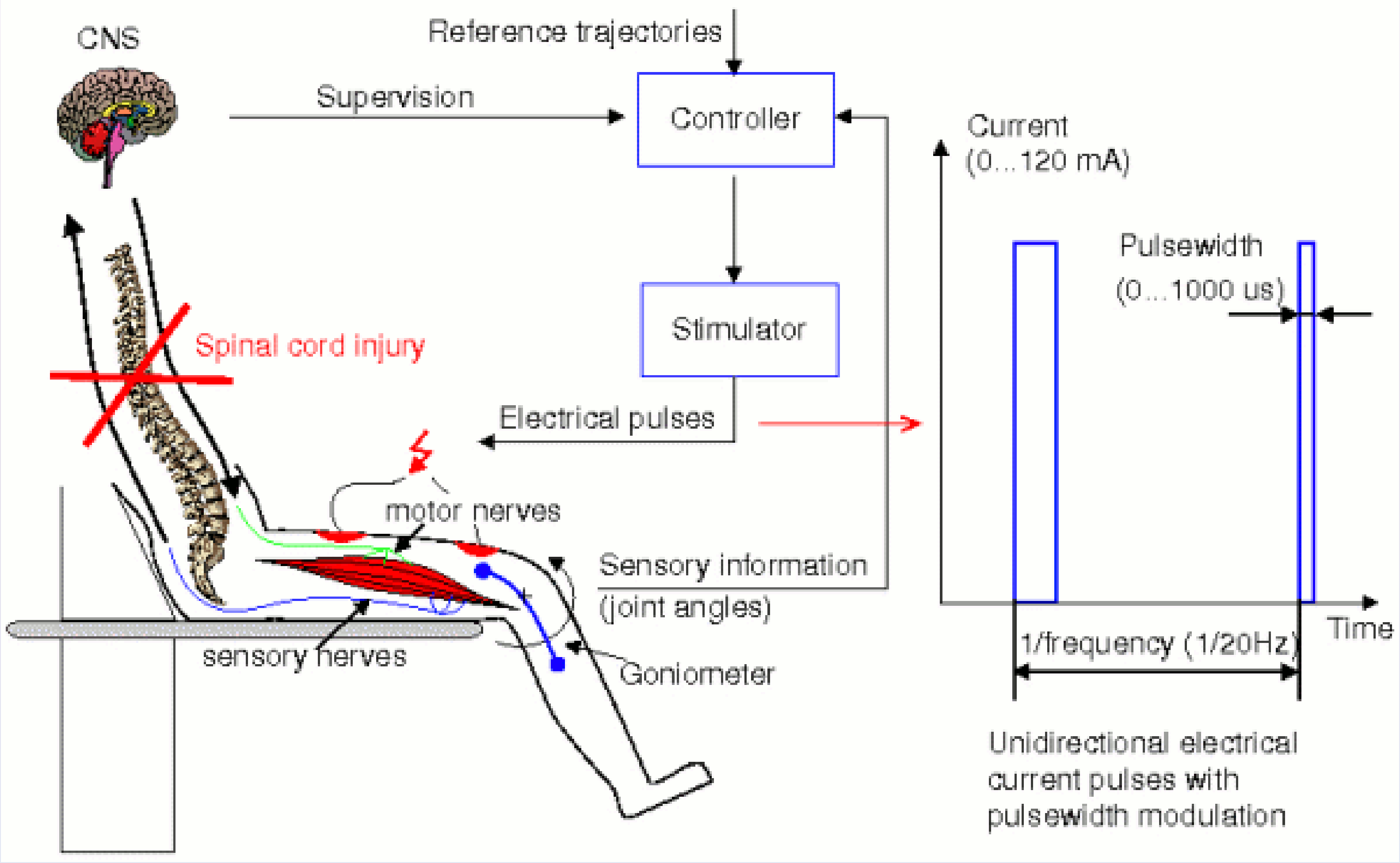
Sensors: Visual Vestibular

Activation of the physiological actuators



Giszter, 2008. Neurotherapeutics

Functional electrical stimulation



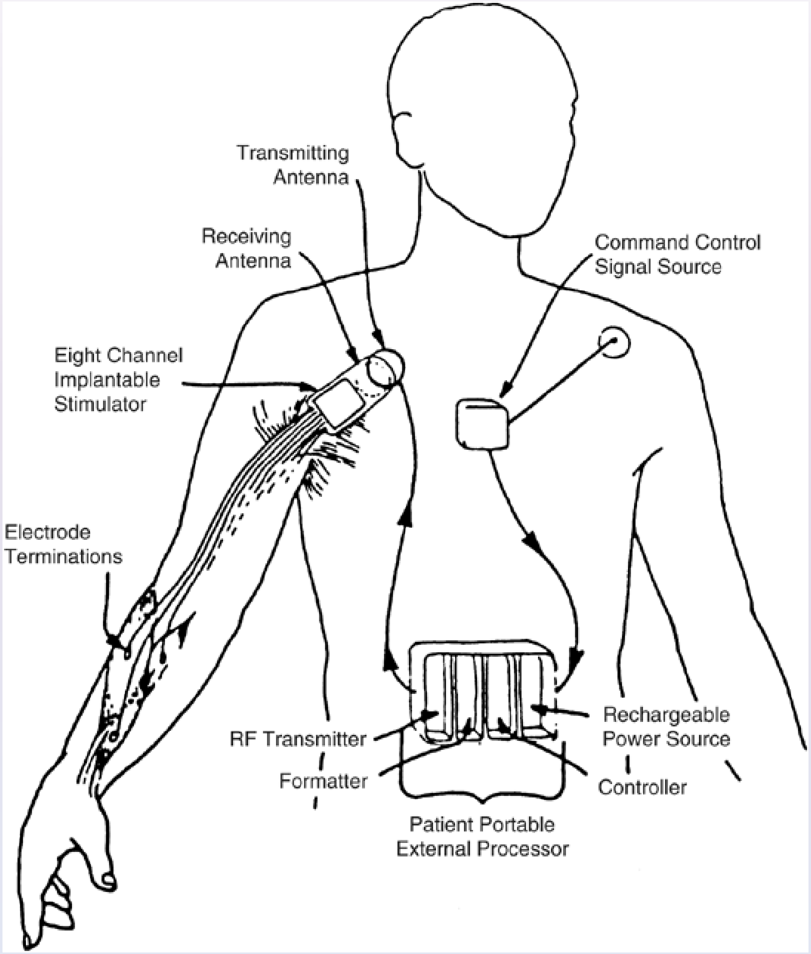
Activation of the physiological actuators

- Electrical current through the nerve:
  - Intracellular
  - Extracellular:
    - Electrical stimulation
    - Magnetic stimulation
- Electrical stimulation
  - Percutaneous
  - Subcutaneous
- Magnetic stimulation

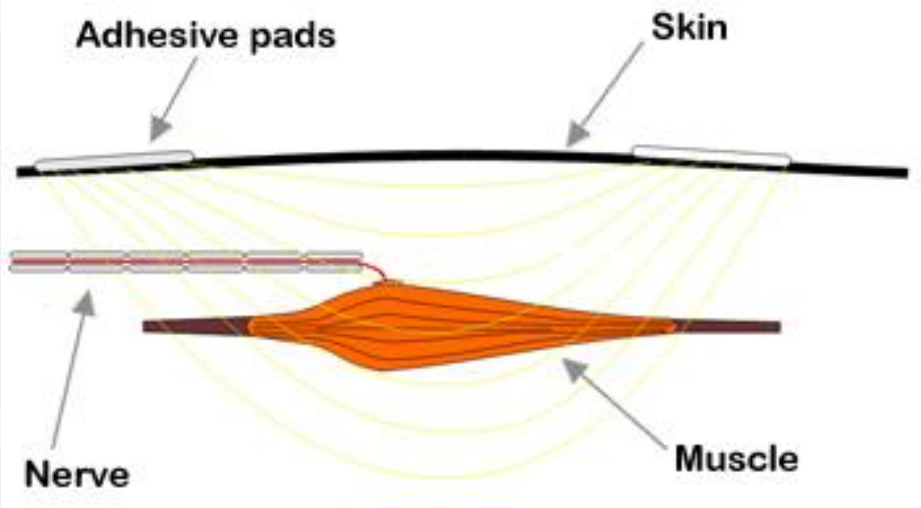
Activation of the physiological actuators

- Excitation of the motoneuron axon
  - Currente density through the tissue:
    - Electrical field
    - Magnetic field
  - Membrane potential must be above the trigger threshold
- Artifical control:
  - Spatial recruitment
    - New electrodes arrays for FES
  - Temporal recruitment

Commercial system



Commercial system



Thanks